Green Transition, Energy Substitution, and Macroeconomic Dynamics in a DSGE Model for Korea*

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Abstract

We study how macroeconomic and energy-related shocks, together with climate-policy design, affect output, inflation, the energy mix, emissions, and distribution in a small energy-importing economy such as Korea. We develop a small open-economy DSGE model with two types of energy: imported fossil-based ("brown") energy and domestically produced renewable ("green") energy. Households directly consume a bundle of brown and green energy, and firms use the same energy composite in production. This structure allows aggregate shocks and policies—operating through the relative price of brown versus green energy—to feed directly into consumption choices, firms' input mix and marginal costs, and hence inflation and output dynamics. Quantitatively, green-technology shocks are expansionary, disinflationary, and carbon-reducing, whereas UIP and brown-energy price shocks are also carbon-reducing but at the cost of stagflation. For a given carbon-tax path, the allocation of revenues has first-order effects on both the output and the inflation dynamics. Monetary policy mainly allocates the burden of shocks between output and inflation, with only minor effects on emissions. The elasticity of substitution between brown and green energy is crucial for the output–emissions trade-off.

Keywords: Green transition, Energy substitution, Carbon tax, Monetary policy
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1 Introduction

Over the past three decades, South Korea's greenhouse gas emissions have risen sharply, increasing by more than about 100 percent relative to 1990 and reaching roughly around 733 Mt CO_2-eq in 2018, before declining to around 649 Mt CO_2-eq in 2023. While this recent downward trend is encouraging, achieving the 2030 Nationally Determined Contribution (NDC) target—a reduction of about 40 percent relative to 2018 levels—will require a profound restructuring of the country's energy system. Figure 1 illustrates the evolution of Korea's electricity generation mix by energy source over the period 2000–2024.[1] As shown in the figure, Korea's energy mix remains dominated by coal and natural gas, complemented by nuclear power and a still modest renewable energy. Even though the share of non-carbon energy has been rising steadily,[2] the renewable energy still remains well below the levels observed in many developed economies.[3]

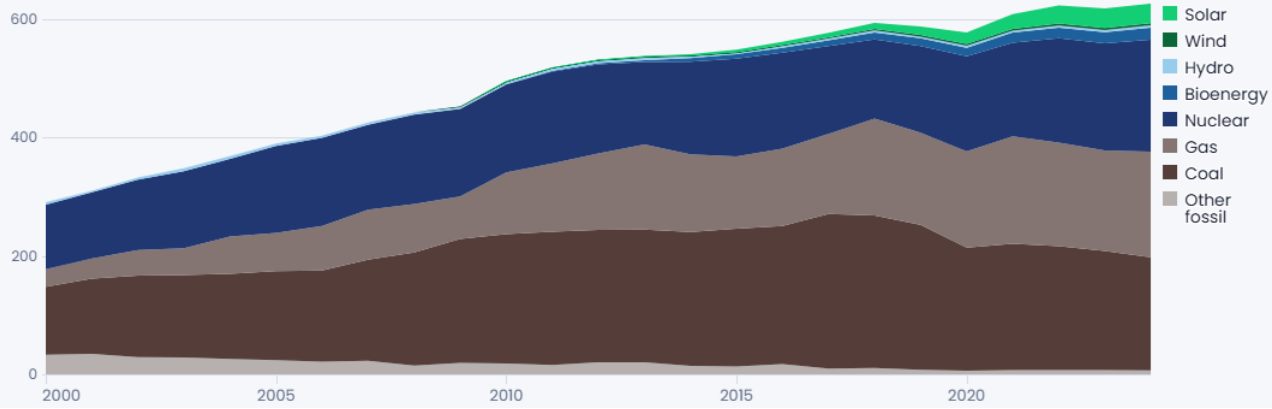


Figure 1: Evolution of Korea's Electricity Generation Mix by Energy Source
Note: Electricity generation by energy source in Korea (Terawatt hours). Figure is from Ember electricity data explorer, ember-energy.org.

In this context, policymakers need a quantitative framework that links macroeconomic and environmental outcomes to macroeconomic and energy-related shocks. We develop such a unified framework for a small, energy-importing economy such as Korea and use it to study how these shocks affect

[1] The figure is from the Ember Electricity Data Explorer (ember-energy.org).

[2] The combined share of renewable and nuclear power has risen from roughly one-third in the mid-2010s to just over 40 percent by the mid-2020s.

[3] According to Global Electricity Review 2024 by Ember, while many OECD countries saw power-sector emissions peak in 2007 and decline by about 28% since then, Korea's emissions only peaked in 2018 and have fallen by roughly 13%. Likewise, the combined share of wind and solar in Korea's electricity generation—around 5%—is far below the global average of about 13 % .

output, inflation, the energy mix, and emissions. Within this framework, we analyze fiscal policy with a focus on the design and implementation of a carbon tax and examine the associated implications for monetary policy.

We build a dynamic stochastic general equilibrium (DSGE) model of a small open economy with two types of energy: fossil-based "brown" energy and renewable "green" energy. The model is calibrated to key features of the Korean economy, where heavy reliance on imported energy, sizable exchange-rate movements, and exposure to global financial conditions are central for understanding business-cycle dynamics and energy mix. The economy also features two types of households—Ricardian (optimizing) and hand-to-mouth (HtM)—who differ in their ability to smooth consumption over time. Both types consume a composite of non-energy goods and energy services, where energy services are themselves a bundle of brown and green energy. This structure makes relative energy prices and climate policies (carbon taxes, green subsidies) directly relevant for household choices over brown versus green energy, while heterogeneity in financial access allows us to study who gains and who loses from shocks and policy reforms. On the production side, non-energy goods are produced by monopolistically competitive firms that use capital, labor, and an energy composite, subject to Calvo price stickiness. Brown energy is imported, whereas green energy is produced by a capital-intensive domestic sector subject to green-technology shocks. An environmental block links brown-energy use in all sectors to the accumulation of atmospheric carbon, and climate damages reduce effective productivity through a damage-adjusted Total Factor Productivity (TFP) term. Monetary policy follows an augmented Taylor rule that can respond to inflation, the output gap, and exchange-rate movements.

Relative to existing small-open-economy and climate–energy DSGE models, a key feature of our framework is explicit substitution between brown and green energy in a small open-economy setting. Households consume an energy composite that combines both fossil-based ("brown") and renewable ("green") energy, rather than being affected by energy only indirectly through goods prices. Firms likewise use both types of energy in production. In an economy that imports brown energy, the relative price of brown versus green energy—shaped jointly by world energy prices, the exchange rate, and domestic climate policies such as carbon taxes and green subsidies—feeds directly into households' consumption choices and firms' input mix. Through these channels, global energy and financial shocks, domestic policy design, and business-cycle conditions jointly determine the energy mix, the

macroeconomic response, and, via emissions, the path of atmospheric carbon and climate damages.

The quantitative analysis yields five main results. First, once the energy and open-economy blocks are taken seriously, different shocks generate sharply distinct joint macro–climate responses. TFP and green-technology shocks are expansionary and disinflationary: they raise output, consumption, and investment while lowering inflation and emissions.[4] In particular, green-technology shocks reduce emissions primarily by making green energy cheaper and gradually shifting the energy mix toward renewables. By contrast, UIP shocks and brown-energy price shocks are stagflationary yet carbon-reducing: they depreciate the currency, raise the domestic price of imported fossil energy, depress real activity, and increase inflation, while inducing a large contraction in brown-energy use and a decline in atmospheric carbon. This contrast highlights the difference between "involuntary decarbonization" driven by adverse external shocks and "deliberate decarbonization" driven by improvements in green technology.

Second, for a given carbon-tax path, the way revenues are redistributed has first-order consequences for the output cost and inflation profile of the policy.[5] All three schemes we consider generate a short-run decline in GDP and a temporary rise in CPI inflation, reflecting higher effective prices of carbon-intensive energy. However, the output loss is clearly smallest when revenues are directed toward supporting green-energy supply. These results suggest that if policymakers' main concern is to minimize the output cost of decarbonization while containing inflationary pressures, revenue designs that strengthen the supply side of the green-energy sector are preferable to pure transfer schemes.

Third, the degree of substitutability between brown and green energy governs the strength of the trade-off between real activity and environmental improvement. When substitution is difficult, brown-energy price and carbon-tax shocks behave like strong adverse supply disturbances: output and investment fall sharply, inflation rises more, and emissions decline mainly because the economy contracts. When substitution is easy, households and firms can shift toward green energy at relatively low cost, so these shocks have much smaller effects on activity and inflation, while the drop in brown-energy use and the carbon stock is driven more by reallocation than by recession. For

[4]The TFP shock leads to an increase in carbon emissions and atmospheric carbon, but the magnitude is quantitatively modest and partly offset by the gradual rebalancing of the energy mix toward green sources.

[5]We consider three revenue-neutral schemes: (i) lump-sum transfers to hand-to-mouth households, (ii) subsidies for green-energy purchases by households and intermediate-goods firms, and (iii) a price subsidy for green-energy producers.

green-technology improvements, all calibrations are pro-growth and pro-environment, but difficult substitution produces the largest output boom, whereas easy substitution yields the largest reduction in emissions.

Fourth, the model reveals distributional implications. Productivity and green-technology shocks are both pro-growth and clearly pro-poor: hand-to-mouth households benefit disproportionately because higher wages and cheaper green energy translate directly into current spending. By contrast, the UIP shock and the brown-energy price shock are approximately distributionally neutral. Thus, whether a shock or policy is "good" or "bad" for the aggregate economy is only part of the story; its incidence across optimizing and liquidity-constrained households can differ sharply, which is also central for evaluating energy and climate policies in an unequal economy.

Finally, monetary policy in this framework primarily allocates the burden of energy and climate shocks between output and inflation, with only second-order effects on emissions and atmospheric carbon. Taylor-rule coefficients therefore matter a great deal for business-cycle stabilization around a given climate policy, but they are not an effective instrument for materially altering environmental outcomes.

Taken together, these results show that the macroeconomic and environmental consequences of the green transition depend critically on the nature of the shock, the structural features of the model—such as the degree of substitutability between brown and green energy—and the fiscal design of carbon taxation. From a policy perspective, this implies that effective climate policy must jointly consider which shocks are driving the transition, how the energy system is organized, and how carbon-tax revenues are allocated, rather than relying solely on the stance of monetary policy or the headline level of the carbon price.

Related Literature

Recently, central banks, international organizations, and academic researchers have been actively developing environmentally-augmented DSGE models to quantitatively assess how climate policies affect inflation, aggregate demand, and monetary policy responses. This literature can be broadly grouped into four strands according to its main focus.

The first strand consists of studies that examine the macroeconomic effects of introducing carbon

taxes. Golosov et al. (2014) study a DSGE model in which fossil-fuel use generates a climate externality and derive a simple formula showing that the marginal external damage from emissions is proportional to current GDP and depends only on discounting, the expected damage elasticity, and carbon decay. Using a multi-sector New Keynesian DSGE model, Del Negro, di Giovanni and Dogra (2023) show that a carbon tax of 20 dollars per ton of CO_2 would raise headline inflation by 2 percentage points and core inflation by 1 percentage point, and that a monetary policy placing strong emphasis on price stability can widen the output gap by up to −8 percentage points. Batten and Millard (2024), using an open-economy DSGE framework, compare a carbon tax of 100 pounds per ton of CO_2 with a ban on fossil fuel use. They find that both policies impose short-run costs on inflation and GDP, but emphasize that the elasticity of substitution in energy use is the key moderating parameter. Treating the carbon tax as a supply shock, they argue that, rather than responding rigidly, the monetary authority can mitigate the downturn by tolerating a certain degree of inflation. Berthold et al. (2023) empirically document the economic effects of carbon pricing policies and develop a theoretical model with green and brown firms that accounts for these patterns and illuminates the underlying transmission mechanisms.

A second strand of the literature compares carbon taxes with subsidy policies or analyzes mixed policy packages that combine the two. Using a small open-economy DSGE model, Airaudo, Pappa and Seoane (2025) compare a carbon tax, subsidies, and a combined tax-plus-subsidy strategy. They find that a stand-alone carbon tax worsens both inflation and output, while a stand-alone subsidy depresses consumption through the accumulation of government debt. By contrast, a mixed policy that recycles tax revenues is evaluated as the optimal alternative, improving both transition dynamics and welfare. Delgado-Téllez, Quintana and Santabárbara (2024) employ a network-DSGE model linking 56 sectors across 61 countries and show that a carbon tax of 100 pounds per ton of CO_2 lowers GDP by 0.4%, but that expanded investment in renewable energy dampens the rise in electricity prices and reduces carbon emissions by up to 24%. They also stress that, while a carbon border adjustment mechanism can curb carbon leakage, it may simultaneously raise the prices of imported intermediate goods, thereby exerting negative effects on GDP and inflation. Dietrich, Leitenbacher and Muller (2026) show that higher carbon prices under the ETS2 raise headline inflation and dampen durable consumption, implying that strict inflation stabilization can slow the shift from brown to green durables. Their results

suggest that while monetary policy affects the pace of the transition, its quantitative role is limited compared with the direct impact of carbon pricing.

A third strand analyzes how monetary and financial policies should be linked to the green transition. Ferrari and Nispi Landi (2023) show that, when a carbon tax is combined with central bank purchases of green assets ("green QE"), the initial emissions reduction can be amplified by 5–8 percentage points, while the impacts on macroeconomic variables can be kept within ±0.1 percentage points. This demonstrates empirically that the composition of monetary policy instruments can substantially change the real effects of climate policy. Priftis and Schoenle (2024) develop an environmentally-augmented DSGE model and argue that certain energy-related fiscal measures may actually increase carbon emissions and delay the green transition. They therefore propose imposing a macroprudential levy on banks' exposures to fossil-fuel firms in order to mitigate these risks and strengthen incentives for private green investment. Such an integration of financial stability and monetary policy considerations highlights how climate risks may need to be internalized within macroprudential and monetary frameworks. Nakov and Thomas (2023) investigate how climate change and policy-driven mitigation efforts interact with monetary policy design in a canonical New Keynesian environment that incorporates climate externalities.

Finally, there has been a recent increase in the development of large-scale integrated models designed to analyze the effects of climate policies at a global level. Carton et al. (2023) develop the GMMET (Global Macroeconomic Model for the Energy Transition), which provides a detailed representation of the fossil fuel, electricity, and transport sectors and enables quantitative analysis of the short- and medium-run effects of various climate policy tools, including carbon taxes, subsidies, and regulatory measures. Chateau et al. (2025) use the IMF–Environment computable general equilibrium (CGE) model, based on data for 160 countries and 76 industrial sectors, to dynamically analyze the medium- to long-term effects of climate, energy, and trade policies on the global economy and industrial structure.

Relative to this literature, we develop an environmentally augmented small open-economy New Keynesian DSGE model with two explicit energy sectors, brown and green. These two inputs are combined into a single energy composite that enters both sides of the economy: households use the energy bundle directly in consumption, while intermediate-goods firms combine it with capital and

labor in production. Brown energy is imported, whereas green energy is produced domestically by a dedicated sector. In this setting, world fossil-fuel prices and the nominal exchange rate pass through directly to domestic energy prices, consumer price inflation, and emissions. This sectoral structure allows us to trace how climate policy and global energy shocks propagate jointly through household demand, firms' costs, and the energy sectors.

Road Map The remainder of the paper is organized as follows. Section 2 presents the model in detail. Section 3 describes the calibration. Section 4 analyzes the effects of key macroeconomic and energy shocks, as well as carbon-tax shocks. Section 5 discusses the role of substitution between brown and green energy and the distributional effects. Section 6 examines the monetary policy implications. Section 7 concludes.

2 Model

This section presents a dynamic stochastic general equilibrium (DSGE) model of a small open economy that imports fossil-based energy ("brown" energy) and produces renewable energy ("green" energy) domestically. The framework is tailored to the Korean economy, where energy import dependence, exchange-rate movements, and heterogeneous households are central for understanding both macroeconomic fluctuations and the transition to a low-carbon economy.

On the demand side, households are heterogeneous in their access to financial markets and in their energy needs. On the supply side, non-energy goods are produced by monopolistically competitive firms using capital, labor, and an energy composite, while green energy is produced by a dedicated domestic sector. Brown energy is imported at a world price that co-moves with the exchange rate. Climate dynamics link brown-energy use to the accumulation of atmospheric carbon. Monetary policy follows an augmented Taylor rule that may react to inflation, the output gap, and nominal exchange-rate movements, and fiscal policy redistributes firm profits via lump-sum transfers. Market clearing conditions tie together domestic allocations, foreign borrowing, and energy imports.

2.1 Households

The economy features two types of households that differ in their ability to smooth consumption: Ricardian (optimizing) households, who have full access to asset markets, and hand-to-mouth (HtM) households, who consume all of their current income each period and do not accumulate wealth. The population share of HtM households is denoted by λ, while Ricardian households comprise the remaining share $1 - \lambda$.

2.1.1 Ricardian (Optimizing) Households

Ricardian households, denoted by s, maximize expected discounted utility:

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left[\frac{(X_t^s)^{1-\sigma} - 1}{1-\sigma} - \chi^s \frac{(N_t^s)^{1+\varphi}}{1+\varphi} \right], \tag{1}$$

where β is the discount factor, X_t^s is composite consumption, and N_t^s is labor supply. The parameter $1/\sigma$ governs the elasticity of intertemporal substitution, φ is the inverse Frisch elasticity, and χ^s controls the disutility of work.

Ricardian household consumption is a constant-elasticity-of-substitution (CES) composite of non-energy consumption C_t^s and energy services E_t^s:

$$X_t^s = \left[(1 - \psi_E^s)^{\frac{1}{\eta^s}} (C_t^s)^{\frac{\eta^s - 1}{\eta^s}} + (\psi_E^s)^{\frac{1}{\eta^s}} (E_t^s)^{\frac{\eta^s - 1}{\eta^s}} \right]^{\frac{\eta^s}{\eta^s - 1}}, \tag{2}$$

where ψ_E^s determines the share of energy in consumption and η^s is the elasticity of substitution between energy and non-energy goods.

Energy services are a CES bundle of brown and green energy,

$$E_t^s = \left[(\psi_{E_B}^s)^{\frac{1}{\eta_E^s}} (E_{B,t}^s)^{\frac{\eta_E^s - 1}{\eta_E^s}} + (1 - \psi_{E_B}^s)^{\frac{1}{\eta_E^s}} (E_{G,t}^s)^{\frac{\eta_E^s - 1}{\eta_E^s}} \right]^{\frac{\eta_E^s}{\eta_E^s - 1}}, \tag{3}$$

where $\psi_{E_B}^s$ measures the share of brown energy and η_E^s controls the substitutability between brown and green energy.

Budget constraint Ricardian households can trade domestic bonds B_t^s, foreign bonds B_t^{s*}, and accumulate physical capital K_t^s. Their nominal budget constraint is

$$P_{Y,t}C_t^s + P_{Y,t}I_t^s + P_{E_B,t}E_{B,t}^s + P_{E_G,t}E_{G,t}^s + B_t^s + \mathcal{E}_t B_t^{s*} + \frac{\phi_B}{2}\mathcal{E}_t P_t^* \left(\frac{B_t^{s*}}{P_t^*} - \frac{B^{s*}}{P^*}\right)^2$$
$$= W_t N_t^s + R_t^k K_{t-1}^s + R_{t-1}B_{t-1}^s + \mathcal{E}_t R^* B_{t-1}^{s*} + \frac{DIV_{Y,t} + DIV_{E,t}}{1-\lambda} - P_t T_t^s, \tag{4}$$

where $\mathcal{E}_t$ is the nominal exchange rate, R_t is the domestic policy rate, R^* the world interest rate, and ϕ_B governs the foreign-asset adjustment cost. Ricardian income consists of wage earnings, capital rental income, bond returns, and dividends from both production sectors, net of lump-sum taxes.

Capital accumulation We assume that Ricardian households face convex investment adjustment costs. Accordingly, capital evolves according to

$$K_t^s = (1-\delta)K_{t-1}^s + \left[1 - \frac{\phi_I}{2}\left(\frac{I_t^s}{I_{t-1}^s} - 1\right)^2\right] I_t^s, \tag{5}$$

where δ is the depreciation rate and ϕ_I controls investment adjustment costs. These costs play a central role in smoothing investment responses to macroeconomic and energy-related shocks.

2.1.2 Hand-to-Mouth Households

Hand-to-Mouth (HtM) households, denoted by h, have no access to asset markets and thus cannot smooth consumption intertemporally. They maximize

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left[\frac{(X_t^h)^{1-\sigma} - 1}{1-\sigma} - \chi^h \frac{(N_t^h)^{1+\varphi}}{1+\varphi}\right], \tag{6}$$

where preferences mirror those of Ricardian households but with type-specific disutility of labor.

HtM composite consumption is

$$X_t^h = \left[(1-\psi_E^h)^{\frac{1}{\eta^h}} (C_t^h)^{\frac{\eta^h-1}{\eta^h}} + (\psi_E^h)^{\frac{1}{\eta^h}} (E_t^h)^{\frac{\eta^h-1}{\eta^h}}\right]^{\frac{\eta^h}{\eta^h-1}}, \tag{7}$$

where ψ_E^h determines the importance of energy in consumption and η^h is the elasticity of substitution between energy and non-energy goods for HtM households.

Energy services for HtM households are

$$E_t^h = \left[(\psi_{E_B}^h)^{\frac{1}{\eta_E^h}} (E_{B,t}^h)^{\frac{\eta_E^h - 1}{\eta_E^h}} + (1 - \psi_{E_B}^h)^{\frac{1}{\eta_E^h}} (E_{G,t}^h)^{\frac{\eta_E^h - 1}{\eta_E^h}} \right]^{\frac{\eta_E^h}{\eta_E^h - 1}}, \tag{8}$$

where $\psi_{E_B}^h$ measures reliance on brown energy and η_E^h controls the substitutability between brown and green energy.

Static budget constraint Because HtM households do not save,

$$P_{Y,t} C_t^h + P_{E_B,t} E_{B,t}^h + P_{E_G,t} E_{G,t}^h = W_t N_t^h + P_t T_t^h. \tag{9}$$

They consume all their current labor income and transfer T_t^h. Thus, their consumption reacts strongly and immediately to wage and transfer fluctuation. This mechanism is central for generating the distributional patterns observed in the impulse-response results.

In our model, we explicitly introduce two energy consumption choices in the household problem, so that energy prices and policy instruments directly affect households' decisions over brown versus green energy. We also allow for imperfect substitution between the two energy types. The elasticity of substitution plays a key role in the quantitative results: a higher elasticity enables households to shift more readily toward renewable energy in response to policy or price shocks. In addition, households are heterogeneous, which allows us to analyze the distributional consequences of shocks of interest—including energy-related shocks and carbon tax policies—across different household types.

2.2 Non-Energy Sector

The non-energy sector follows a standard two-tier structure. A representative final-goods firm aggregates a continuum of differentiated intermediate goods into a homogeneous final good. Intermediate-goods firms operate under monopolistic competition and produce using capital, labor, and an energy composite that combines brown and green energy, while facing nominal price stickiness (e.g., Calvo

pricing).

2.2.1 Final-Goods Firm

A representative, perfectly competitive final-goods firm aggregates a continuum of differentiated non-energy intermediate goods $Y_t(j)$, $j \in [0,1]$, into a homogeneous final good Y_t. The aggregation technology is given by a constant-elasticity-of-substitution (CES) production function:

$$Y_t = \left(\int_0^1 Y_t(j)^{\frac{\varepsilon-1}{\varepsilon}} \, dj \right)^{\frac{\varepsilon}{\varepsilon-1}}, \tag{10}$$

where $\varepsilon > 1$ denotes the elasticity of substitution across intermediate varieties.

The final-good firm takes as given the set of intermediate-good prices $\{P_{Y,t}(j)\}_{j\in[0,1]}$ and the final-good price $P_{Y,t}$, and chooses $\{Y_t(j)\}_{j\in[0,1]}$ to minimize the cost of producing a given level of the final good Y_t. The cost-minimization problem gives us the standard demand function for each variety:

$$Y_t(j) = \left(\frac{P_{Y,t}(j)}{P_{Y,t}} \right)^{-\varepsilon} Y_t, \tag{11}$$

where $P_{Y,t}$ is the sectoral price index, which is the minimum unit cost of producing one unit of the final good and thus the aggregate price index for the CES bundle.

The corresponding price index consistent with cost minimization is

$$P_{Y,t} = \left(\int_0^1 P_{Y,t}(j)^{1-\varepsilon} \, dj \right)^{\frac{1}{1-\varepsilon}}. \tag{12}$$

2.2.2 Intermediate-Goods Firm

Intermediate-goods firms operate under monopolistic competition. Each firm j uses capital $K_t^y(j)$, labor $N_t^y(j)$, and an energy composite $E_t^y(j)$ according to

$$Y_t(j) = \widetilde{A}_t \left[(1-\alpha_E)^{\frac{1}{\zeta}} \left(K_t^y(j)^{\alpha_K} N_t^y(j)^{1-\alpha_K} \right)^{\frac{\zeta-1}{\zeta}} + \alpha_E^{\frac{1}{\zeta}} (E_t^y(j))^{\frac{\zeta-1}{\zeta}} \right]^{\frac{\zeta}{\zeta-1}}, \tag{13}$$

where $\widetilde{A}_t$ is damage-adjusted aggregate productivity, α_K is the capital share within the capital–labor bundle, α_E is the energy share in production, and ζ is the elasticity of substitution between the capital–labor composite and the energy composite.

The energy composite $E_t^y(j)$ is a CES aggregator of brown and green energy:

$$E_t^y(j) = \left[\alpha_{E_B}^{\frac{1}{\zeta_E}} (E_{B,t}^y(j))^{\frac{\zeta_E - 1}{\zeta_E}} + (1 - \alpha_{E_B})^{\frac{1}{\zeta_E}} (E_{G,t}^y(j))^{\frac{\zeta_E - 1}{\zeta_E}} \right]^{\frac{\zeta_E}{\zeta_E - 1}}, \tag{14}$$

where α_{E_B} is the brown-energy share in production and ζ_E is the elasticity of substitution between brown and green energy in production. This elasticity is the production-side counterpart of η_E^i in household demand and is crucial in the sensitivity experiments: higher ζ_E implies that firms can more easily re-optimize their energy mix when the relative price of brown energy changes.

Profits in this sector are

$$DIV_{Y,t} = \int_0^1 \left[P_{Y,t}(j) Y_t(j) - W_t N_t^y(j) - R_t^k K_t^y(j) - P_{E_B,t} E_{B,t}^y(j) - P_{E_G,t} E_{G,t}^y(j) \right] dj. \tag{15}$$

A key feature of the intermediate-goods sector is that productivity is directly affected by the atmospheric carbon stock. The term $\widetilde{A}_t$ captures the impact of climate damages on technology and is decreasing in the carbon stock S_t, as specified in the environmental block. Hence, an increase in S_t reduces $\widetilde{A}_t$ and shifts down the marginal product of all inputs, implying that higher carbon concentrations in the atmosphere depress total factor productivity in the non-energy production sector.[6]

A second key feature is that intermediate-goods firms use an energy composite as a separate input in production. This composite bundles brown and green energy, so that both types of energy enter the firm's cost structure. As a result, the relative price of brown versus green energy—which is shaped by energy markets, climate policy instruments, and exchange rates—directly affects firms' input choices, marginal costs, and thus the optimal price they charge for their differentiated variety. This channel is central for understanding how energy and climate policies propagate through the production sector into aggregate inflation and output dynamics.

[6]The detailed functional form of $\widetilde{A}_t$ as a function of S_t is discussed later.

Price Setting Prices are sticky à la Calvo. In each period, a fraction θ of firms keep their previous price, while the remaining share $1-\theta$ reoptimizes. A reoptimizing firm sets a reset price $P_{Y,t}^{\#}$ that maximizes the expected discounted value of profits subject to future demand conditions. The optimal reset price satisfies

$$P_{Y,t}^{\#} = \frac{\varepsilon}{\varepsilon - 1} \frac{\mathbb{E}_t \sum_{k=0}^{\infty} (\beta^s \theta)^k \Lambda_{t+k}^s MC_{t+k} Y_{t+k} (P_{Y,t+k})^{\varepsilon}}{\mathbb{E}_t \sum_{k=0}^{\infty} (\beta^s \theta)^k \Lambda_{t+k}^s Y_{t+k} (P_{Y,t+k})^{\varepsilon}}, \tag{16}$$

where Λ_{t+k}^s is the Ricardian household's stochastic discount factor and MC_{t+k} is nominal marginal cost.

2.3 Energy Sector

The energy sector consists of two components: imported brown energy and domestically produced green energy. This distinction is central to both the small-open-economy and climate-policy dimensions of the model. Brown energy is imported from the rest of the world at a given foreign-currency price, so any exogenous change in the world price of brown energy directly affects its domestic price. In addition, because purchases are denominated in foreign currency, movements in the nominal exchange rate also pass through to the domestic brown-energy price.

By contrast, green energy is produced domestically. It is governed by its own production technology and is assumed to be relatively capital-intensive. As a result, shocks to its own production technology matter for the relative cost of green versus brown energy through general-equilibrium effects. This structure allows the model to capture how external shocks jointly shape the energy mix, production costs, and ultimately macroeconomic and climate outcomes.

2.3.1 Brown Energy

Brown energy is imported from the rest of the world at an exogenous foreign-currency price $P_{E_B,t}^*$. Its domestic-currency price is given by

$$P_{E_B,t} = \mathcal{E}_t P_{E_B,t}^*, \tag{17}$$

where $\mathcal{E}_t$ denotes the nominal exchange rate, defined as the domestic-currency price of one unit of foreign currency. Thus, any movement in either the world price $P^*_{E_B,t}$ or the nominal exchange rate $\mathcal{E}_t$ immediately passes through to the domestic-currency price of brown energy.

The corresponding real price of brown energy, expressed in units of the domestic consumption price index (CPI) P_t, is

$$p_{E_B,t} \equiv \frac{P_{E_B,t}}{P_t} = \mathcal{E}_t \frac{P^*_{E_B,t}}{P_t} = \mathcal{Q}_t \, p^*_{E_B,t}, \tag{18}$$

where

$$\mathcal{Q}_t \equiv \mathcal{E}_t \frac{P^*_t}{P_t} \tag{19}$$

is the real exchange rate (an increase corresponds to a real depreciation), P^*_t is the foreign price level, and

$$p^*_{E_B,t} \equiv \frac{P^*_{E_B,t}}{P^*_t} \tag{20}$$

is the world real price of brown energy in terms of the foreign CPI. This decomposition highlights that the domestic real price of brown energy is jointly driven by external energy-price conditions $p^*_{E_B,t}$ and domestic-real-exchange-rate movements $\mathcal{Q}_t$.

We assume that the world real price of brown energy follows a persistent AR(1) process:

$$p^*_{E_B,t} = (1 - \rho_B)\, \bar{p}^*_{E_B} + \rho_B \, p^*_{E_B,t-1} + \sigma_B \, \varepsilon_{B,t}, \tag{21}$$

where $\bar{p}^*_{E_B}$ is the steady-state world real price, $\rho_B \in (0, 1)$ measures the persistence of global brown-energy price fluctuations, $\sigma_B > 0$ scales the size of shocks, and $\varepsilon_{B,t}$ is an i.i.d. innovation capturing global brown-energy price shocks.

On the supply side, the small open economy takes the world price $p^*_{E_B,t}$ as given and faces a perfectly elastic foreign supply of brown energy at that price. Formally, for any domestic demand for brown energy arising from households and firms, the rest of the world can supply the required quantity at the prevailing world price. As a result, domestic brown-energy quantities are demand-determined, while the domestic real price $p_{E_B,t} = \mathcal{Q}_t p^*_{E_B,t}$ is shaped by (i) exogenous global energy-price shocks $\varepsilon_{B,t}$ and (ii) endogenous exchange-rate movements $\mathcal{Q}_t$ driven by uncovered interest parity (UIP) shocks elsewhere in the model.

This structure implies that global energy shocks and exchange-rate fluctuations feed directly into domestic brown-energy prices, thereby affecting the energy mix, marginal costs in the production sector, households' energy-consumption choices, and, through emissions, the evolution of the atmospheric carbon stock and climate damages. This tight pass-through from world prices and the exchange rate to domestic energy prices is a defining feature of the small open economy in our model.

2.3.2 Green Energy

Green energy is produced domestically by a competitive sector using a dedicated capital stock K_t^e and sector-specific productivity $A_{G,t}$. Output of green energy, $E_{G,t}$, is given by

$$E_{G,t} = A_{G,t}\left(K_t^e\right)^{\alpha_G}, \tag{22}$$

where $\alpha_G \in (0, 1]$ governs the capital intensity in the green sector.[7] The process $A_{G,t}$ captures green-technology productivity; innovations to $A_{G,t}$ represent *green-technology shocks*, such as improvements in renewable generation or storage technologies. Because green energy is capital-intensive, the adjustment of the dedicated capital stock K_t^e over time implies that the supply of green energy responds gradually to shocks. In particular, changes in the rental rate of capital R_t^k, which in a small open economy are influenced by global financial conditions and domestic policy affect the cost of installing and holding K_t^e, and hence the dynamic path of $E_{G,t}$.

Let $P_{E_G,t}$ denote the domestic-currency price of green energy. Profits in the green-energy sector are given by

$$DIV_{E,t} = P_{E_G,t}E_{G,t} - R_t^k K_t^e. \tag{23}$$

Under perfect competition and constant returns to scale in (22), equilibrium profits are driven to zero, so $P_{E_G,t}$ equals the marginal cost of producing green energy. In this case, higher rental rates R_t^k or lower green productivity $A_{G,t}$ increase the marginal cost and thus the relative price of green energy.

Taken together with the imported brown-energy block, this structure implies that the relative price of green versus brown energy is shaped by two distinct channels: (i) external forces and exchange-

[7] When $\alpha_G < 1$, the green-energy technology exhibits decreasing returns with respect to K_t^e at the firm or sector level; this helps pin down equilibrium profits and the scale of the sector.

rate movements that determine the domestic price of imported brown energy, and (ii) domestic capital-market conditions and green-technology shocks that determine the cost of producing green energy at home. These channels are central for understanding how global energy shocks and domestic financial conditions interact to affect the energy mix, marginal costs, and ultimately macroeconomic and climate outcomes in a small open economy.

2.4 Climate Dynamics

Our environmental block follows the existing climate–macro literature (e.g., Golosov et al., 2014; Nakov and Thomas, 2023): we adopt a standard carbon-depreciation and emissions-accumulation structure, and specify the carbon process and damage function in line with these contributions. The atmospheric carbon stock S_t evolves according to

$$S_t = (1-\vartheta)S_{t-1} + \vartheta_0\Big(\lambda E^h_{B,t} + (1-\lambda)E^s_{B,t} + E^y_{B,t}\Big), \tag{24}$$

where ϑ_0 is the fraction of emissions that remain in the atmosphere and $1-\vartheta$ governs the decay rate of carbon.[8] Emissions are proportional to brown-energy use in all sectors—HtM households, Ricardian households, and intermediate-goods firms—so any policy or shock that changes brown-energy demand translates directly into carbon-stock dynamics.

Climate damages enter the model through a damage-adjusted aggregate productivity term, $\widetilde{A}_t$, defined as

$$\widetilde{A}_t = \Big[1 - D_t(S_t)\Big]A_t, \tag{25}$$

where A_t denotes exogenous total factor productivity and $D_t(S_t) \in [0,1)$ is the damage function capturing output losses from climate change as a function of the atmospheric carbon level S_t. We specify the damage term via

$$1 - D_t(S_t) = \exp\Big(-\omega^{KR}(S_t - \bar{S})\Big), \tag{26}$$

[8] We interpret the atmospheric carbon stock as the relevant stock affecting the Korean economy, rather than the global economy as a whole.

where $\omega^{KR} > 0$ is an elasticity parameter governing the sensitivity of effective productivity in Korea to deviations of carbon from its steady-state level, $\bar{S}$.[9] Under this specification, a higher atmospheric carbon concentration S_t relative to $\bar{S}$ lowers the damage-adjusted productivity $\widetilde{A}_t$ through the exponential term, thereby reducing effective output for given factor inputs.

2.5 Monetary Authority

Monetary policy is conducted by a central bank that follows an augmented Taylor rule:

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\rho_R} \left[\left(\frac{\pi_t}{\pi}\right)^{\phi_\pi} \left(\frac{Y_t}{Y}\right)^{\phi_Y} \left(\frac{\mathcal{E}_t}{\mathcal{E}_{t-1}}\right)^{\phi_E}\right]^{1-\rho_R}, \tag{27}$$

where R is the steady-state nominal interest rate, π is steady-state inflation, and Y is steady-state output. The parameter ρ_R captures interest-rate smoothing, while ϕ_π, ϕ_Y, and ϕ_E measure the responsiveness of the policy rate to deviations of inflation, output, and nominal exchange-rate growth, respectively. This specification allows us to study: (i) standard inflation targeting; (ii) output-gap stabilization; and (iii) FX-reaction rules, which are relevant for a small open economy with "fear of floating".[10]

2.6 Fiscal Authority

In our economy, we consider a simple progressive tax system. The government levies taxes on corporate profits and redistributes the proceeds to households in the form of lump-sum transfers. In the baseline model without carbon taxation, the main fiscal role of the government is therefore to redistribute profits from the production sector back to households.

Let $DIV_{Y,t}$ and $DIV_{E,t}$ denote profits (dividends) from the non-energy and green-energy sectors, respectively. A fraction $\tau_d \in [0, 1]$ of aggregate profits

$$DIV_{Y,t} + DIV_{E,t}$$

[9] Or, $\bar{S}$ can be interpreted as a pre-industrial or policy-target benchmark.

[10] We do not use the steady-state nominal exchange rate in the policy rule, as it has little practical relevance. Instead, we target the gross change in the nominal exchange rate relative to the previous period, which also helps to ensure determinacy of the equilibrium.

is collected as profit tax revenue. This revenue is then rebated to households as lump-sum transfers. We distinguish between Ricardian (saving) households, indexed by s, and hand-to-mouth (HtM) households, indexed by h. Aggregate taxes and transfers (in nominal terms) to the two groups, $P_t T_t^s$ and $P_t T_t^h$, are given by

$$P_t T_t^s = (1-\lambda)\,\tau_d\Big(DIV_{Y,t} + DIV_{E,t}\Big), \tag{28}$$

$$P_t T_t^h = \lambda\,\tau_d\Big(DIV_{Y,t} + DIV_{E,t}\Big), \tag{29}$$

where $\lambda \in [0,1]$ governs the share of tax revenues rebated to HtM households. Thus, HtM households receive a fraction λ of total profit-tax revenue, while Ricardian households receive the remaining fraction $1-\lambda$. This rule implies that fluctuations in profits—for example, due to TFP shocks, green-technology shocks, energy-price shocks, or changes in the carbon stock that affect damage-adjusted productivity $\widetilde{A}_t$—translate into variations in lump-sum transfers to each household group. Through (28)–(29), these profit fluctuations generate a redistribution channel that influences consumption, saving, and portfolio decisions in a heterogeneous-agent setting.

In later extensions of the model, we introduce an explicit carbon tax on brown-energy use. We then specify in detail how carbon-tax revenues are allocated across transfers, potential green subsidies, and other fiscal instruments, and compare the macroeconomic, environmental, and distributional implications.

2.7 Market Clearing and External Balance

Aggregate conditions close the model and highlight its small open economy structure.

Goods-market clearing requires

$$Y_t = C_t + I_t, \tag{30}$$

where aggregate consumption and investment are

$$C_t = \lambda C_t^h + (1-\lambda) C_t^s, \tag{31}$$

$$I_t = (1-\lambda) I_t^s. \tag{32}$$

The green-energy market clears when total supply equals total demand:

$$E_{G,t} = \lambda E^h_{G,t} + (1-\lambda)E^s_{G,t} + E^y_{G,t}. \tag{33}$$

Labor market clearing equates labor demanded by firms with the sum of hours supplied by both household types:

$$N^y_t = \lambda N^h_t + (1-\lambda)N^s_t. \tag{34}$$

The total capital stock used by non-energy and green-energy firms equals Ricardian's capital holdings:

$$K^y_t + K^e_t = (1-\lambda)K^s_t. \tag{35}$$

Ricardian households hold zero net domestic bonds in equilibrium, $B^s_t = 0$, so their intertemporal smoothing operates through foreign bonds and physical capital. Foreign-asset flows satisfy

$$(1-\lambda)\left[\mathcal{E}_t B^{s*}_t - \mathcal{E}_t R^* B^{s*}_{t-1} + \frac{\phi_B}{2}\mathcal{E}_t P^*_t \left(\frac{B^{s*}_t}{P^*_t} - \frac{B^{s*}}{P^*}\right)^2\right] = -P_{E_B,t}\Big(\lambda E^h_{B,t} + (1-\lambda)E^s_{B,t} + E^y_{B,t}\Big). \tag{36}$$

The left-hand side represents net purchases of foreign assets (plus adjustment costs) by Ricardian households. The right-hand side is the economy's total spending on imported brown energy. Thus, the external balance condition ties foreign borrowing and lending directly to energy imports, providing the key channel through which brown-energy price shocks and UIP shocks interact with the domestic macroeconomy and the energy–climate block.

3 Calibration

This section describes the calibration of the parameters in the benchmark economy. One model period corresponds to a quarter. Table 1 reports the parameter values used in the benchmark model and summarizes the mapping between parameters and empirical targets or external sources.

We first calibrate the household-side parameters using standard values from the literature. The quarterly discount factor is set to $\beta = 0.99$, which implies a steady-state real return on capital of approximately 1% per quarter. This choice is standard in the small-open-economy DSGE literature. The

Table 1: Parameters of the Benchmark Economy

Parameter	Value	Description	Target Moments/Source
		Households	
β	0.99	Time discount factor	Real capital return
σ	1.0	Risk aversion	Standard
ϕ	1.0	Inverse Frisch elasticity	Standard
λ	0.3	Share of HtM	Jung and Yang (2025)
ψ_E	0.1	Share of energy in X	See text
η	0.25	Substitutability b/w $E\&C$	See text
ψ_{E_B}	0.6	Share of brown energy	See text
η_E	2.3	Substitutability b/w $E_B\&E_G$	See text
ϕ_B	0.001	Foreign-asset adj. cost	Standard
ϕ_I	2.0	Investment adj cost	Standard
δ	0.015	Capital depreciation	Standard
		Firms	
ε	11	Substitutability b/w $Y(j)$	Standard
α_E	0.04	Energy share	See text
α_K	0.3	Capital share	Standard
ζ	0.25	Substitutability b/w $(K,L)\&E^y$	See text
α_{E_B}	0.6	Brown-energy share	See text
ζ_E	2.3	Substitutability b/w $E^y_B\&E^y_G$	See text
θ	0.75	Calvo pricing	Standard
α_G	0.8	Capital share in Green sector	See text
		Climate Dynamics and Policy	
ϑ	0.003	Decay parameter	Golosov et al. (2014)
ϑ_0	0.5	Emission parameter	Golosov et al. (2014)
ω^{KR}	$4.8e^{-7}$	Damage parameter	See text
ρ_R	0.8	Smoothing parameter	Standard
ϕ_π	1.5	Weight on inflation	Standard
ϕ_Y	0.25	Weight on output	Standard
ϕ_E	0	Weight on FX rate	See text
τ_d	0.1	Tax rate on dividend	See text

coefficient of relative risk aversion is set to $\sigma = 1$, corresponding to logarithmic utility in consumption, which facilitates comparison with existing studies that adopt similar preferences. The inverse Frisch elasticity of labor supply is set to $\phi = 1$, which yields a unit Frisch elasticity and realistic labor-supply responses at the aggregate level.[11] To ensure stationarity of net foreign assets, we introduce a small quadratic adjustment cost on foreign asset holdings and set the foreign-asset adjustment-cost parameter to $\phi_B = 0.001$. This value is sufficiently small so as not to distort the model's dynamics,

[11] We choose the disutility-of-labor parameter so that steady-state hours worked are one-third of the time endowment for both Ricardian and hand-to-mouth households.

while guaranteeing a well-defined steady state. Investment is subject to convex adjustment costs, captured by the parameter ϕ_I. In line with standard medium-scale DSGE models, we set $\phi_I = 2$, which generates empirically plausible dynamics for investment and the capital stock in response to shocks.

Next, we calibrate the parameters on the production side, again relying on standard values from the literature. The elasticity of substitution across intermediate goods is set to $\varepsilon = 11$, which implies a steady-state gross price markup of $\varepsilon/(\varepsilon - 1) \approx 1.10$ (about a 10% markup), a conventional value in the New Keynesian literature. The capital income share in the production function of the non-energy sector is set to $\alpha_K = 0.3$, consistent with national-account estimates for Korea and with typical values used in macroeconomic models. Nominal rigidities are introduced through Calvo-style price stickiness. The Calvo price-adjustment parameter is set to $\theta = 0.75$, implying that in each quarter only 25% of firms can reset their prices. This corresponds to an average price duration of $1/(1-\theta) = 4$ quarters.

Monetary policy follows an interest-rate rule with interest-rate smoothing and responses to inflation and the output gap. The interest-rate smoothing parameter is set to $\rho_R = 0.8$, capturing the gradual adjustment of the policy rate over time. The coefficients on inflation and the output gap are set to $\phi_\pi = 1.5$ and $\phi_Y = 0.25$, respectively, ensuring that the Taylor principle is satisfied and that the policy rule stabilizes inflation and real activity. In the benchmark specification, the central bank does not respond directly to the nominal exchange rate, so we set $\phi_E = 0$.[12] Finally, the tax rate on dividend income is set to 10 percent.

We next turn to the calibration of Korea-specific parameters that govern energy use, household heterogeneity, and climate dynamics. We impose two simplifying assumptions to keep the model tractable. First, energy-related preference parameters are assumed to be identical across household types (Ricardian and hand-to-mouth households).[13] This assumption implies that, conditional on their income and wealth, both household types share the same preferences over energy and non-energy consumption, as well as the same elasticity of substitution between these components. Second, we assume that the elasticities of substitution and the energy-related share parameters are common

[12] These monetary-policy parameters are consistent with structural estimates for Korea reported by Jung and Yang (2025).

[13] Formally, $\psi_E^s = \psi_E^h = \psi_E, \quad \psi_{E_B}^s = \psi_{E_B}^h = \psi_{E_B}, \quad \eta^s = \eta^h = \eta, \quad \eta_E^s = \eta_E^h = \eta_E.$

to both households and firms.[14] These restrictions substantially reduce the dimensionality of the parameter space and ensure a consistent treatment of energy throughout the model.

On the household side, the share of hand-to-mouth workers is set to 0.3, in line with empirical evidence on the fraction of liquidity-constrained households in Korea (Jung and Yang, 2025). Based on Korean micro-level data as in Jung (2013), the share of energy in total consumption expenditure is approximately 10%; we therefore set $\psi_E = 0.1$. Following Berthold et al. (2023), we set the elasticity of substitution between energy and non-energy consumption to $\eta = 0.25$, which implies a high degree of complementarity between energy and other consumption goods. This choice is also in line with the Integrated Assessment Model (IAM) literature (see, for example, Luderer et al., 2020).

The composition of energy use between brown and green sources is calibrated to match recent Korean data. According to statistics on electricity generation, the share of carbon-based energy in total energy use is approximately 60% in our baseline period.[15] In the model, this corresponds to setting $\psi_{E_B} = \alpha_{E_B} = 0.6$, so that 40% of energy use is accounted for by green (low-emission) sources. The quarterly capital depreciation rate is set to $\delta = 0.015$, implying an annual depreciation rate of about 6%. This value is consistent with empirical estimates for Korea based on national-account.

A key parameter governing the transition from brown to green energy is the elasticity of substitution between green and brown energy, η_E. Berthold et al. (2023) use $\eta_E = 1.5$, while Nakov and Thomas (2023) consider higher values around $\eta_E = 3.0$. We choose an intermediate value and set $\eta_E = 2.3$, which is similar to the estimate by Papageorgiou, Saam and Schulte (2017). This choice implies that green and brown energy are neither perfect complements nor close substitutes, allowing relative price movements induced by climate policy to generate meaningful but not excessive substitution between them. As mentioned above, we assume the same elasticity for firms, so that $\eta_E = \zeta_E = 2.3$. We later examine the role of this parameter in detail by considering alternative values.

On the production side, the energy share in the non-energy sector's production function is set to $\alpha_E = 0.04$ following Golosov et al. (2014), which reflects the relatively modest but non-negligible role of energy in aggregate production.[16] We assume that the green-energy sector is capital intensive,

[14] Accordingly, we impose $\psi_{E_B} = \alpha_{E_B}, \quad \eta = \zeta, \quad \eta_E = \zeta_E$.

[15] See https://www.iea.org/countries/korea/electricity.

[16] This value is also consistent with calibrated energy-sector models in the Korean context, including Park (2013).

mirroring the high fixed costs and large investment requirements associated with renewable energy technologies. Accordingly, we set the capital share in green-energy production to $\alpha_G = 0.8$, which implies that variations in the user cost of capital have a strong impact on the supply of green energy.

Finally, we calibrate the parameters governing climate dynamics. The law of motion for the carbon stock and the damage function follow Golosov et al. (2014), so the parameters (ϑ, ϑ_0) that govern natural carbon decay and the pre-industrial carbon level are taken directly from their study. Let ω^{world} denote the global damage scale parameter and $\omega^{\text{world}} = 2.4 \times 10^{-5}$ the global damage elasticity in Golosov et al. (2014). Since Korea accounts for roughly 1% of global CO_2 emissions, we scale the damage parameter proportionally and set $\omega^{\text{KR}} = 0.02 \times \omega^{\text{world}}$.[17] This ensures that the costs of climate damages in the model are commensurate with Korea's contribution to global emissions, while preserving the overall curvature of the damage function implied by the global calibration.

Overall, this calibration strategy combines standard parameter values from the international DSGE literature with Korea-specific information on household behavior, energy use, and emissions, thereby enabling a quantitatively meaningful assessment of energy and climate policies in the Korean context.

4 Transmission of Macro Shocks

4.1 Non-Energy Shocks

4.1.1 TFP Shocks

Figure 2 reports impulse responses of key macro, climate, and energy variables to a 1 percent, mean-reverting TFP shock.[18] The first four panels display standard real variables—output (real GDP), consumption, investment, and hours worked—while the rest of the panels show atmospheric carbon and the use of brown and green energy.[19] As in a conventional RBC model, a positive productivity shock raises overall production and expenditure. Output increases in a hump-shaped manner, peaking at roughly 1.2 percent above steady state around four quarters after the shock and then gradually converging back. Consumption also rises, with a smaller peak of about 0.8 percent, and displays

[17] See https://srv1.worldometers.info/co2-emissions/south-korea-co2-emissions.
[18] We set the persistence of all shocks to 0.8.
[19] All variables are expressed as percentage deviations from the steady state, and the horizontal axis is in quarters.

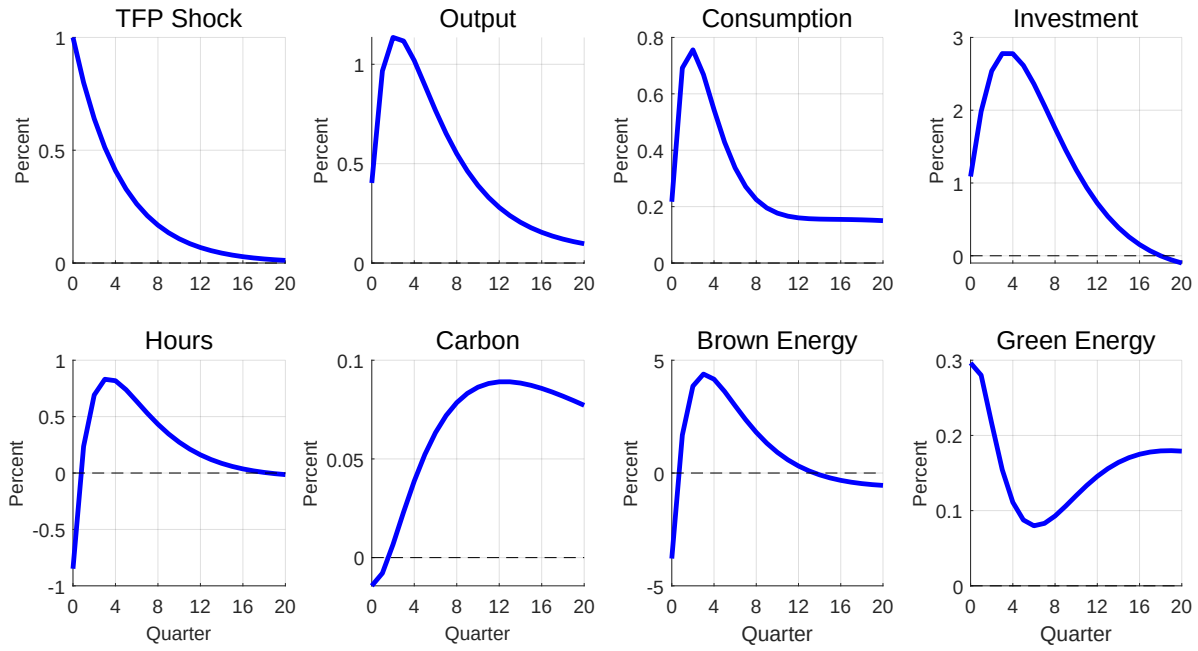


Figure 2: Impulse Responses to a TFP Shock: Real, Climate, and Energy Quantitiess

Note: Impulse responses to a 1 percent TFP shock. The top row and the first panel of the bottom report output (real GDP), consumption, investment, and hours worked. The rest of the bottom row report the stock of atmospheric carbon, brown-energy use, and green-energy use. All variables are measured as percent deviations from the steady state, with the horizontal axis in quarters.

a smoother, more persistent response. Investment is strongly procyclical and much more volatile, reaching close to 2.7 percent at its peak, with the delay reflecting investment-adjustment costs. Hours worked exhibit a short-run drop on impact, but quickly rebound and rise to about 0.7 percent above steady state after four quarters, before slowly declining.

The lower panels highlight the implied dynamics for climate and the energy mix. Brown-energy use responds on impact, falling by more than 2 percent, but then gradually recovers. Green-energy use also increases on impact, though by less, then drops back toward steady state over the first year before partially recovering and stabilizing at a modest positive deviation. Atmospheric carbon responds very sluggishly: it barely moves on impact, then gradually builds up to a peak of about 0.08 percent above steady state after roughly three years, and subsequently declines only very slowly.[20]

Figure 3 reports the responses of factor price-related variables and inflation rates to a 1 percent TFP shock. The top row displays real wages, the real return on capital, and the real exchange rate (RER), while the bottom row shows four inflation measures: CPI inflation, goods-price inflation, and

[20] As mentioned above, we interpret the atmospheric carbon stock as the stock that matters for the Korean economy, rather than for the global economy as a whole.

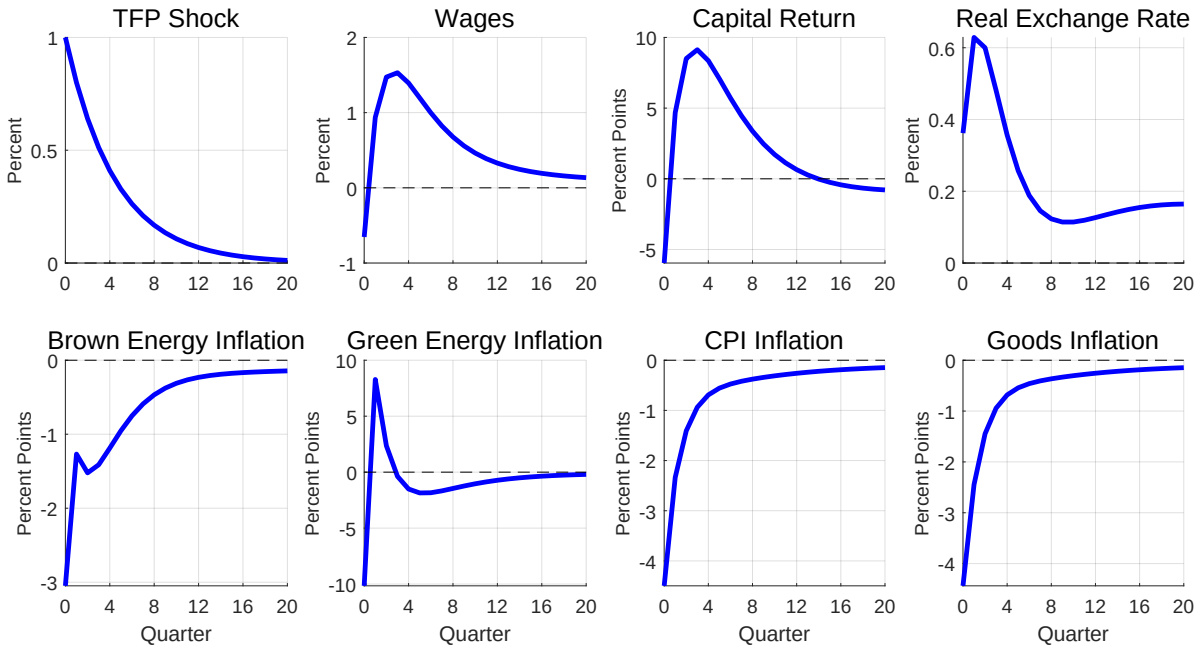


Figure 3: Impulse Responses to a TFP Shock: Factor Prices, Exchange Rate, and Inflation

Note: Impulse responses of price-related variables to a 1 percent TFP shock. The top row shows real wages, the real return on capital, and the real exchange rate. The bottom row shows inflation rates for brown energy, green energy, the CPI, and final goods. Wages and RER are expressed in percent deviations from steady state, whereas the return and the inflation variables are in percentage-point deviations, with the horizontal axis in quarters.

the inflation rates of brown and green energy.[21] Real wages and the real return on capital both fall on impact but then increase sharply, reaching peaks of about 1.5 percent and 8 percent point, respectively. The real exchange rate also rises on impact—reflecting low domestic bond return—overshoots in the short run, and then slowly returns toward its initial level.[22] This real depreciation arises because the positive TFP shock is deflationary: it lowers inflation, triggers a monetary-policy easing under the Taylor rule, and thereby reduces the domestic real interest rate, inducing capital outflows and weakening the domestic currency in real terms.

Consistent with an outward shift of the aggregate supply curve, all inflation measures decline following the positive TFP shock. CPI inflation drops by about 4 annualized percentage points on impact and then slowly reverts toward zero, and goods-price inflation exhibits a very similar pattern. Brown-energy inflation also becomes negative, but its decline is smaller in magnitude than that of CPI and goods inflation, implying that brown-energy prices fall by less than the general price level.

[21] Wages and RER are expressed in percent deviations from steady state, whereas the return and the inflation variables are in percentage-point deviations.

[22] A rise in the real exchange rate (RER) corresponds to a real depreciation of the domestic currency relative to the rest of the world.

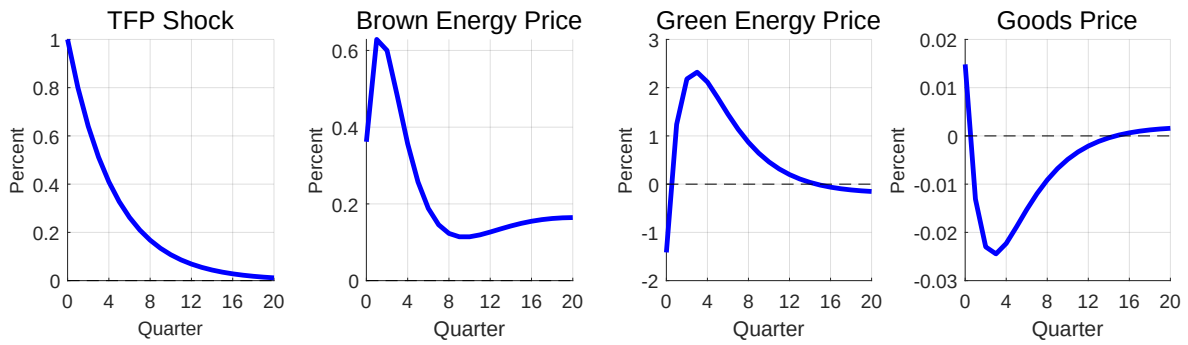


Figure 4: Relative Price Responses to a TFP Shock (Normalized by CPI)

Note: Relative price responses to a 1 percent TFP shock. The figure reports the prices of brown energy, green energy, and final goods normalized by the CPI index, so each panel displays the impulse response of a relative price (in percentage) to CPI over quarters.

By contrast, green-energy inflation shows a short-lived spike in the first quarter, followed by a sizable and persistent decline.

Mechanism Figure 4 further clarifies the dynamics behind the responses of brown and green energy usage and their inflation rates. The figure plots the impulse responses of the prices of brown energy, green energy, and final goods relative to the CPI, so that each series can be interpreted as a deviation of a relative price (in percentage) following a 1-percent TFP shock. This figure is particularly informative, as it summarizes the key adjustments in relative prices that drive the energy-demand and inflation dynamics in the model.

The relative price of brown energy rises on impact by about 0.7 percentage points and remains above its steady-state level in the medium run. This increase is largely driven by the real depreciation of the domestic currency, which makes imported brown energy more expensive in real domestic-currency terms. As explained above, a positive TFP shock lowers inflation, which induces the central bank to cut the policy rate so that real bond returns fall. The lower relative return on domestic assets leads to a real depreciation of the domestic currency, making imported goods more expensive; as a result, the domestic price of imported brown energy rises. The higher relative price of brown energy helps explain why brown energy demand contracts on impact despite the expansion in aggregate activity. By contrast, the relative price of green energy initially falls—reflecting the decline in factor costs in the green sector after the TFP shock—but then rises sharply as higher real GDP boosts the demand for green energy; over time, this effect dissipates and the relative price gradually returns

toward its steady state.[23] Finally, the relative price of the goods price index declines and remains below its initial level in the medium run, consistent with an overall reduction in production costs and cheaper domestic energy inputs compared with the broader CPI basket.

In summary, a positive TFP shock in this model generates broadly standard real-business-cycle dynamics: output, consumption, investment, and hours all increase. Wages and the real return on capital rise, while all inflation measures fall on impact, reflecting an outward shift of the aggregate supply curve. The open-economy and energy blocks, however, introduce important additional channels. The RER increases, which raises the domestic price of imported brown energy relative to the CPI and moderates the expansion of brown-energy demand. At the same time, lower domestic factor costs and stronger activity initially reduce, and then gradually increase, the relative price of green energy, so that green-energy use becomes persistently higher in the medium run. As a result, the TFP shock leads to a increase in carbon emissions and atmospheric carbon, but the magnitude is quantitatively modest and partly offset by the gradual rebalancing of the energy mix toward green sources. Taken together, these results suggest that productivity-driven expansions are disinflationary and that relative-price movements—via the exchange rate and sectoral factor prices—play a key role in shaping the transition from brown to green energy.

4.1.2 UIP Shocks

Since the model features a small open economy with an endogenous real exchange rate, it is natural to examine the effects of disturbances to the uncovered interest parity (UIP) condition. In the international macro and finance literature, such UIP shocks are typically interpreted as exogenous movements in the country–specific risk premium faced by domestic borrowers in global financial markets. In the model, we introduce these shocks as an exogenous risk–premium component in the foreign-bond optimality condition, which alters the effective return on foreign borrowing at given foreign interest rates and expected exchange-rate movements. UIP disturbance appears as a wedge in the standard UIP relation, shifting the spread between domestic and foreign returns independently of fundamentals.

Figure 5 reports the responses of macro, climate, and energy variables to a 1 percent UIP shock

[23] In other words, TFP shocks indirectly affect the price of green energy.

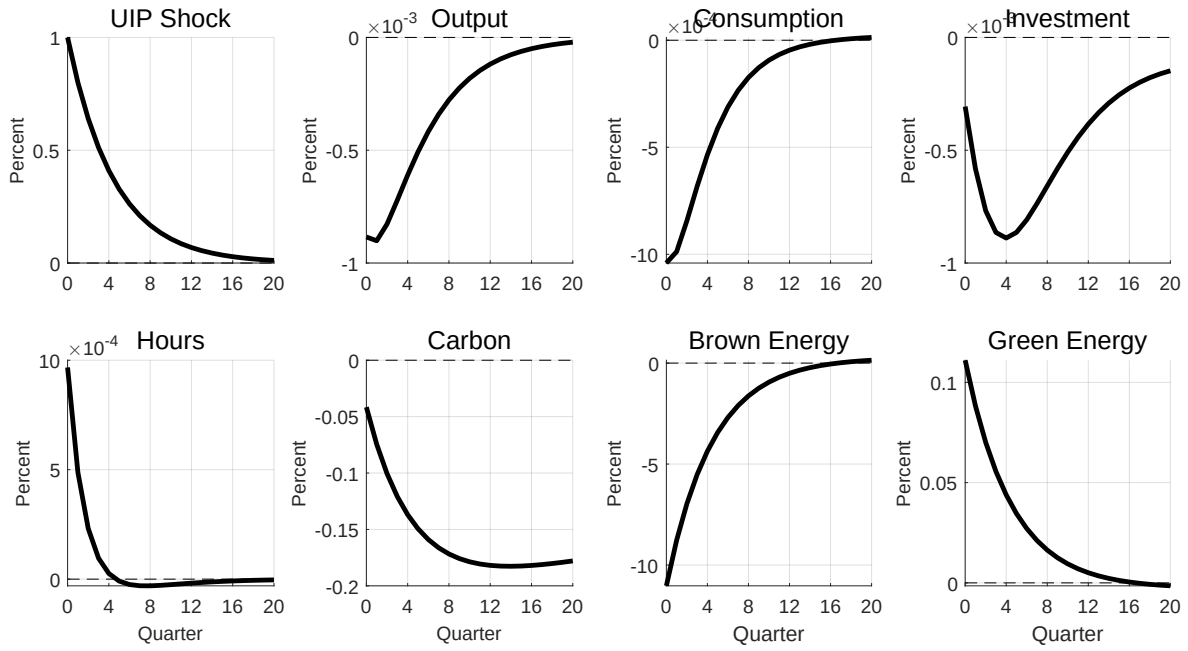


Figure 5: Impulse Responses to a UIP Shock: Real, Climate, and Energy Quantities

Note: Impulse responses to a 1 percent UIP (risk-premium) shock. The top row and the first panel of the bottom report output (real GDP), consumption, investment, and hours worked. The rest of the bottom row report the stock of atmospheric carbon, brown-energy use, and green-energy use. All variables are measured as percent deviations from the steady state, with the horizontal axis in quarters.

that induces a real depreciation of the domestic currency. The first four panels display output, consumption, investment, and hours worked; the last three show atmospheric carbon and the use of brown and green energy. The shock is contractionary. Output and consumption both decline on impact and then gradually mean-revert. Investment falls, remaining below its steady state for several years. Hours worked also increase, but by a comparatively small amount.

The energy block shows a strong reallocation of the energy mix. Brown-energy use drops sharply—by about 10 percent on impact—and then slowly returns toward its initial level, while green-energy use increases modestly. Atmospheric carbon declines steadily, with the carbon stock about 0.17 percent below steady state after five years. Thus, a UIP shock that depreciates the currency is strongly contractionary and substantially reduces fossil-fuel use and carbon emissions in this model.

Figure 6 depicts the responses of factor price-related variables and inflation variables. The top row shows real wages, the real return on capital, and the RER; the bottom row shows the inflation rates of brown energy, green energy, the CPI, and final goods. Following the UIP shock, the RER jumps by around 5 percent and then decays gradually, indicating a sizable but transitory real depreciation. Real wages fall slightly on impact and then slowly recover, consistent with weaker labor demand in

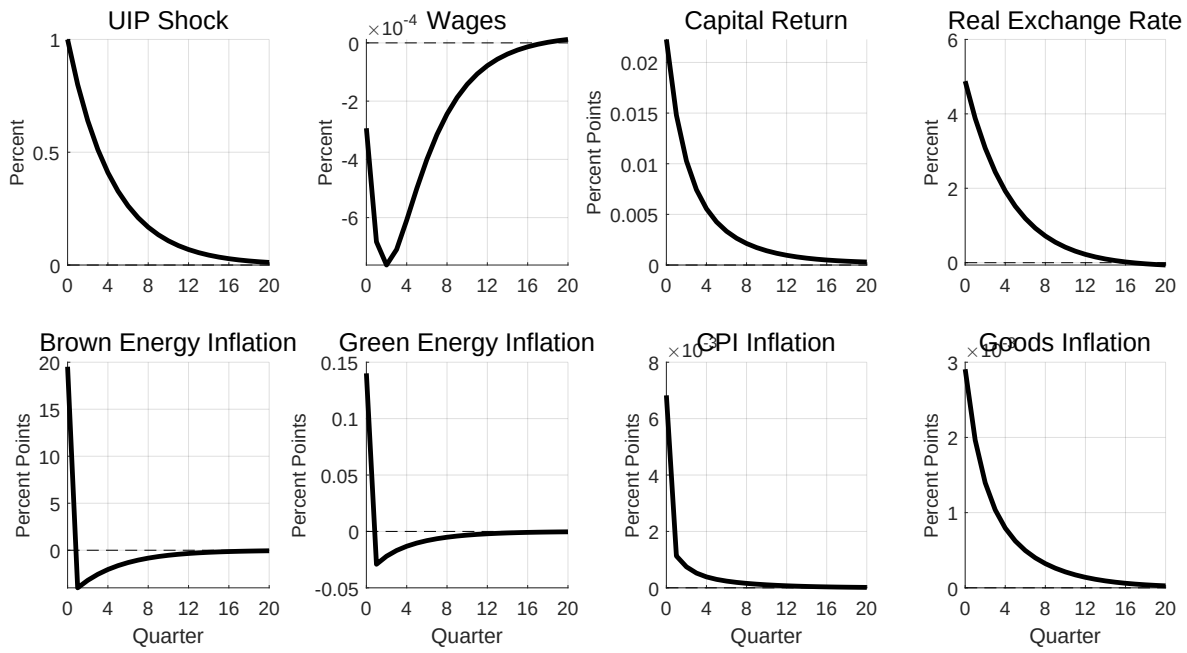


Figure 6: Impulse Responses to a UIP Shock: Factor Prices, Exchange Rate, and Inflation

Note: Impulse responses of price-related variables to a 1 percent UIP shock. The top row shows real wages, the real return on capital, and the real exchange rate. The bottom row shows inflation rates for brown energy, green energy, the CPI, and final goods. Wages and RER are expressed in percent deviations from steady state, whereas the return and the inflation variables are in percentage-point deviations, with the horizontal axis in quarters.

the recession. In contrast, the real return on capital rises modestly on impact and then declines.

The real depreciation feeds quickly into domestic prices. Brown-energy inflation spikes strongly on impact before converging back to zero, indicating a very sharp but short-lived increase in fossil-fuel prices. Green-energy inflation also rises on impact, though by much less, and then quickly returns close to zero. CPI and goods inflation both increase modestly on impact and then decay monotonically. Hence, the UIP shock is mildly inflationary in terms of aggregate price indices, even though it depresses real activity.

To highlight the role of relative prices, Figure 7 plots the responses of brown-energy, green-energy, and goods prices relative to the CPI, so that each series can be interpreted as an impulse response of a relative price (in percentage-point deviations) to the UIP shock.

The relative price of brown energy rises markedly—by almost 5 percentage on impact—and then declines gradually. This large increase in the relative cost of imported fossil energy explains the pronounced contraction in brown-energy demand seen in Figure 5.[24] The relative price of green energy also increases, but by a much smaller amount, so that green energy becomes only slightly more expen-

[24] In equilibrium, the UIP wedge is absorbed mainly through a real depreciation of the domestic currency.

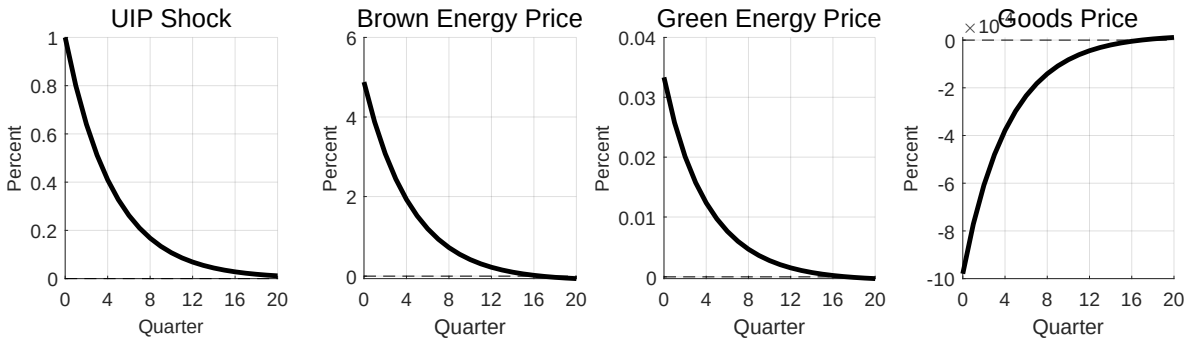


Figure 7: Relative Price Responses to a UIP Shock (Normalized by CPI)

Note: Relative price responses to a 1 percent UIP shock. The figure reports the prices of brown energy, green energy, and final goods normalized by the CPI index, so each panel displays the impulse response of a relative price (in percentage) to CPI over quarters.

sive than the CPI basket. In contrast, the relative price of final goods falls, indicating that non-energy goods become relatively cheaper compared with the overall consumption basket. Overall, the UIP shock mainly operates through a large relative appreciation of imported fossil-energy prices.

A positive UIP (risk-premium) shock in this model is best interpreted as a financial disturbance that induces a real depreciation and raises the domestic-currency price of imported energy. Unlike a TFP shock, it is unambiguously **stagflationary**: output, consumption, investment, and hours all fall, while CPI and goods inflation pick up modestly. At the same time, the sharp increase in the relative price of brown energy leads to a substantial and persistent contraction in fossil-fuel use, a mild expansion of green-energy use, and a gradual decline in the stock of atmospheric carbon. These results imply that external financial disturbances that depreciate the currency can, in principle, reduce emissions by making fossil energy more expensive, but they do so at the cost of a recession and higher consumer prices. In other words, UIP-type shocks deliver "involuntary decarbonization" driven by adverse terms-of-trade movements rather than by deliberate policy.

4.2 Energy-related Shocks

4.2.1 Brown-energy Price Shocks

We next consider a brown-energy price shock, modeled as an exogenous increase in the international price of imported fossil energy faced by domestic agents.[25] Brown-energy price shocks are interpreted

[25] To isolate the pure terms-of-trade effect, we hold the real exchange rate fixed ex ante, so that the shock operates only through the foreign-currency price of brown energy rather than through exchange-rate movements.

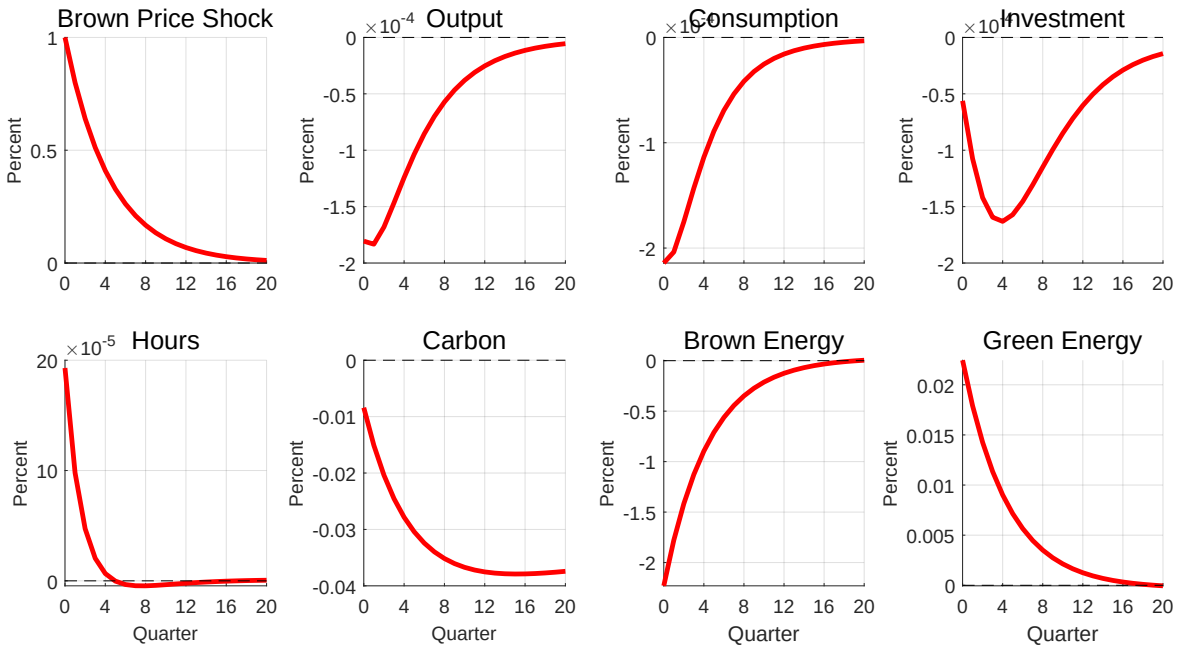


Figure 8: Impulse Responses to a Brown-energy price Shock: Real, Climate, and Energy Quantitiess

Note: Impulse responses to a 1 percent Brown-energy price shock. The top row and the first panel of the bottom report output (real GDP), consumption, investment, and hours worked. The rest of the bottom row report the stock of atmospheric carbon, brown-energy use, and green-energy use. All variables are measured as percent deviations from the steady state, with the horizontal axis in quarters.

broadly: they capture not only increases in energy prices due to geopolitical risks and other supply disruptions, but also higher import prices arising from measures such as carbon border adjustment mechanisms. Figure 8 reports the impulse responses of macro, climate, and energy quantities to a 1 percent brown-energy price shock. The top row and the first panel of the bottom row show output, consumption, investment, and hours worked; the rest of the bottom row show atmospheric carbon, brown-energy use, and green-energy use. All variables are expressed as percent deviations from the steady state.

The shock is mildly contractionary in real terms. Output and consumption fall on impact and then gradually revert toward their initial levels, with investment showing a somewhat larger but still quantitatively small decline. Hours worked display only a very small positive response, remaining close to their steady state throughout. By contrast, the energy variables respond much more visibly: brown-energy use drops by around 2l percentage on impact and then slowly recovers, while green-energy use increases slightly. As a result, the stock of atmospheric carbon declines monotonically over the horizon considered. Figure 9 displays the responses of factor prices, the real exchange rate, and inflation rates to the same brown-energy price shock. Real wages decline slightly and then slowly

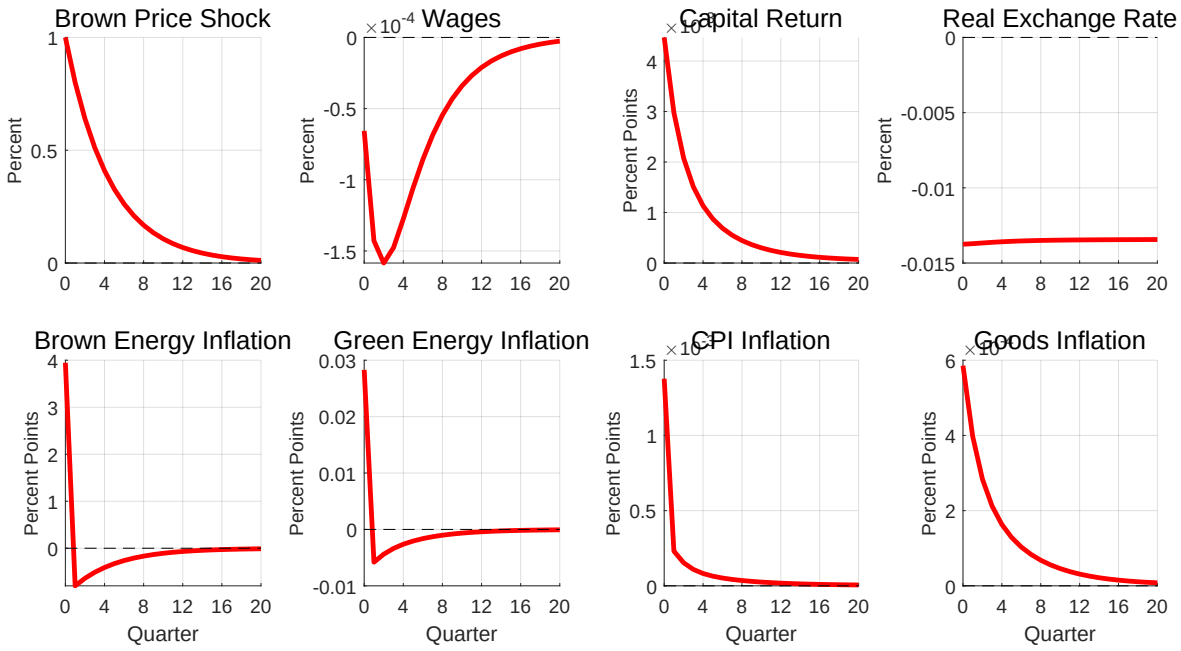


Figure 9: Impulse Responses to a Brown-energy price Shock: Factor Prices, Exchange Rate, and Inflation

Note: Impulse responses of price-related variables to a 1 percent Brown-energy price shock. The top row shows real wages, the real return on capital, and the real exchange rate. The bottom row shows inflation rates for brown energy, green energy, the CPI, and final goods. Wages and RER are expressed in percent deviations from steady state, whereas the return and the inflation variables are in percentage-point deviations, with the horizontal axis in quarters.

return toward their initial level, while the real return on capital increases modestly on impact and decays over time. Movements in the real exchange rate are small in magnitude, indicating that most of the adjustment occurs through domestic prices rather than through large changes in relative international prices. Inflation reacts much more strongly: brown-energy inflation exhibits a sharp spike on impact, green-energy inflation also rises but by a much smaller amount, and both CPI and goods inflation increase modestly before converging back toward zero. Thus, the brown-energy price shock acts as a classic cost-push disturbance—raising inflation while only slightly depressing real activity.

Figure 10 plots the responses of brown-energy, green-energy, and final-goods prices normalized by the CPI. The relative price of brown energy rises sharply on impact, reflecting the direct effect of the external price disturbance. The relative price of green energy also increases, but by a smaller amount. This reflects the rise in demand for green energy discussed above. By contrast, the relative price of final goods falls slightly below its initial level.

In sum, a brown-energy price shock in this model behaves like an imported cost-push (oil-price) shock: it generates a mild contraction in output and demand, a noticeable increase in inflation, and a

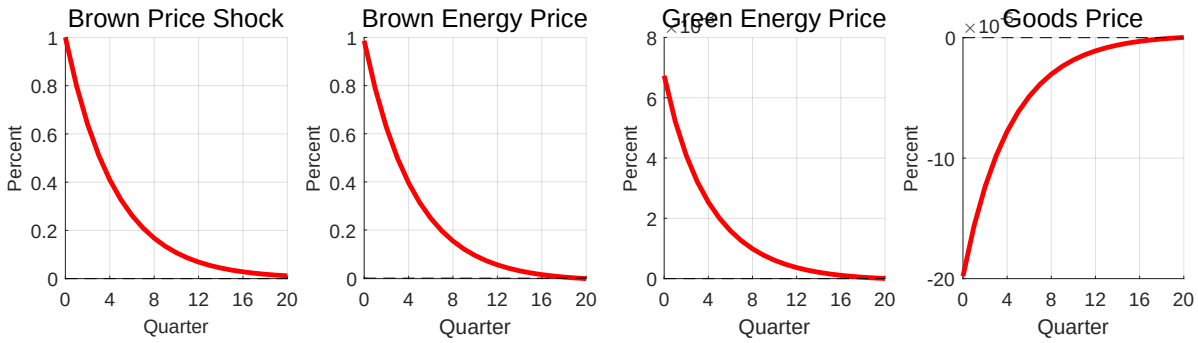


Figure 10: Relative Price Responses to a Brown-energy price Shock (Normalized by CPI)
Note: Relative price responses to a 1 percent Brown-energy price shock. The figure reports the prices of brown energy, green energy, and final goods normalized by the CPI index, so each panel displays the impulse response of a relative price (in percentage) to CPI over quarters.

large deterioration in the relative price of fossil energy. At the same time, the higher relative cost of brown energy induces a reallocation of the energy mix away from fossil fuels toward green sources and leads to a gradual decline in atmospheric carbon. Consequently, decarbonization is achieved here through a stagflationary channel—higher inflation and slightly lower activity—rather than through productivity gains or deliberate policy.

4.2.2 Green Technology Shocks

We next examine a green-technology shock, modeled as an exogenous improvement in productivity in the domestic green-energy sector. Figure 11 reports the impulse responses of macro, climate, and energy quantities to a 1 percent green-technology shock. The shock is expansionary but modest in scale. Output, consumption, and investment all increase on impact, with output rising by about 0.01 percent and consumption by roughly 0.015 percent before gradually returning toward their steady states. Investment exhibits a slightly less pronounced, short-lived riser. Hours worked also increase, though the magnitude is very small and the adjustment is very short-lived. The improvements in green technology generate a clear shift in the energy mix. Green-energy use rises on impact by approximately 0.3 percent, reflecting both the direct productivity gain and substitution away from fossil fuels. Brown-energy use falls sharply by more than 2 percent initially, with a slow mean reversion over time. As a result, total carbon emissions decline: atmospheric carbon decreases steadily, reaching roughly 0.04 percent below steady state after five years.

Figure 12 shows the responses of factor price and inflation variables to the same shock. The im-

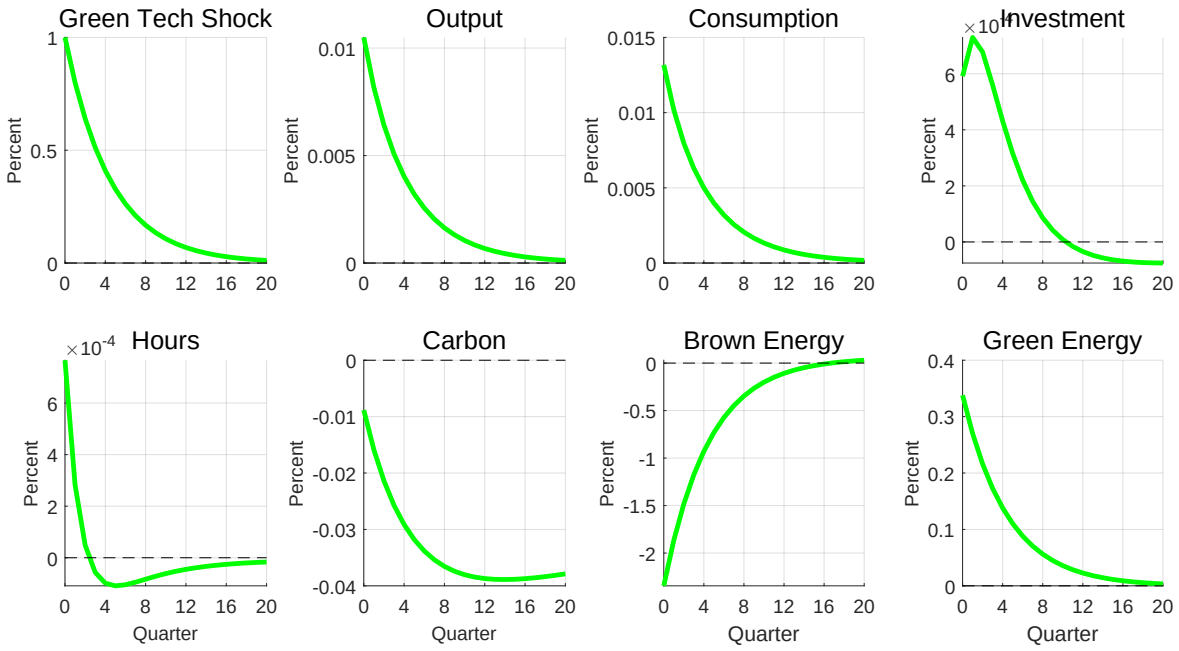


Figure 11: Impulse Responses to a Green Technology Shock: Real, Climate, and Energy Quantitiess

Note: Impulse responses to a 1 percent Green technology shock. The top row and the first panel of the bottom report output (real GDP), consumption, investment, and hours worked. The rest of the bottom row report the stock of atmospheric carbon, brown-energy use, and green-energy use. All variables are measured as percent deviations from the steady state, with the horizontal axis in quarters.

provement in green-energy productivity raises marginal products in the economy, which translates into a short-lived increase in wages of roughly 0.02 percent on impact. The return to capital also falls a bit. The real exchange rate falls, which in our convention corresponds to a real appreciation of the domestic currency.[26] Inflation rates fall across the board. Brown-energy inflation is modestly negative on impact (around –0.1 percentage points), while green-energy inflation drops very sharply—by almost 5 percentage points—because the productivity improvement directly lowers the marginal cost of green energy. CPI and final-goods inflation both decline and then monotonically converge back to zero. Overall, the green-technology shock is deflationary but is accompanied by a real appreciation.

To highlight how the shock alters relative prices, Figure 13 plots the prices of brown energy, green energy, and final goods normalized by the CPI index. The domestic price of brown energy falls on impact by about 0.025 percent. This decrease is driven by the real appreciation: a lower RER decreases real price of imported fossil energy. By contrast, the relative price of green energy drops

[26]This real appreciation arises because the positive green-technology shock is expansionary yet mildly deflationary: it raises output, lowers inflation, and induces the central bank to tighten policy, attracting capital inflows and appreciating the currency in real terms. However, the appreciation is modest, and its sign and magnitude could change under alternative calibrations, depending on the relative strength of the output and inflation responses.

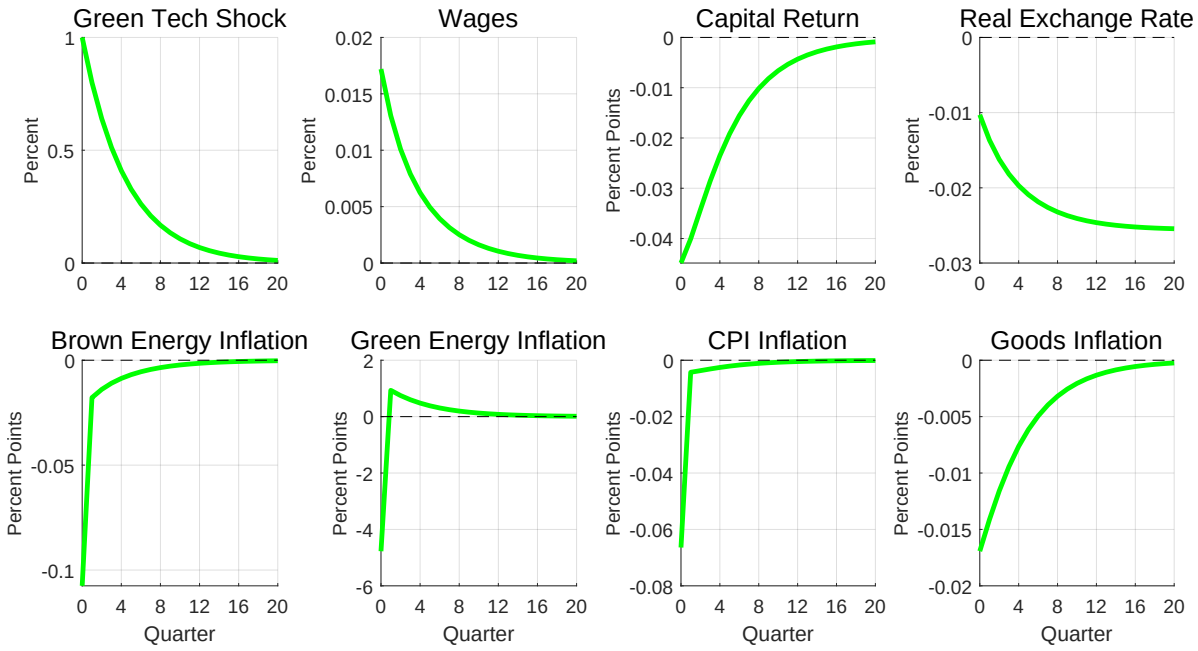


Figure 12: Impulse Responses to a Green Technology Shock: Factor Prices, Exchange Rate, and Inflation

Note: Impulse responses of price-related variables to a 1 percent Green technology shock. The top row shows real wages, the real return on capital, and the real exchange rate. The bottom row shows inflation rates for brown energy, green energy, the CPI, and final goods. Wages and RER are expressed in percent deviations from steady state, whereas the return and the inflation variables are in percentage-point deviations, with the horizontal axis in quarters.

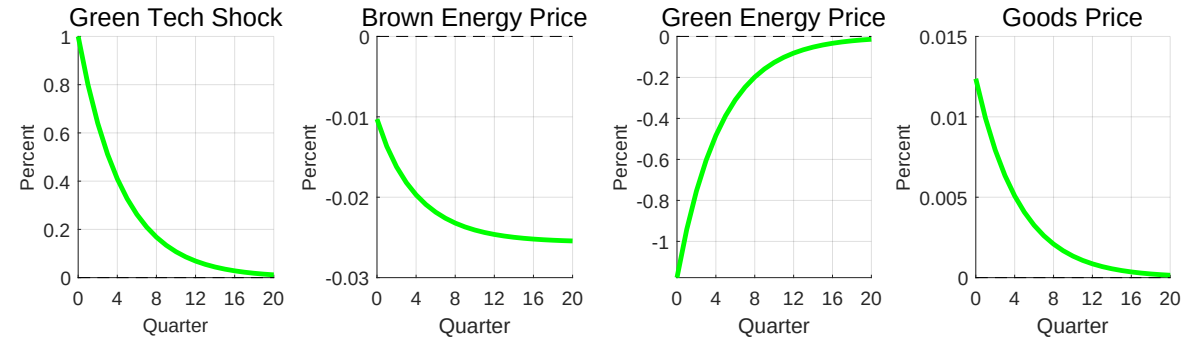


Figure 13: Relative Price Responses to a Green Technology Shock (Normalized by CPI)

Note: Relative price responses to a 1 percent Green technology shock. The figure reports the prices of brown energy, green energy, and final goods normalized by the CPI index, so each panel displays the impulse response of a relative price (in percentage) to CPI over quarters.

sharply—more than 1 percent on impact—reflecting the direct effect of higher productivity in the green-energy sector. However, the relative final-goods price rises.

Overall, the green-technology shock simultaneously (i) boosts real activity, (ii) induces a large and persistent shift from brown to green energy, (iii) lowers aggregate and sectoral inflation, and (iv) generates a weak appreciation that decreases the relative domestic price of imported fossil energy. This combination of effects illustrates how progress in clean energy can deliver both modest macroeco-

nomic gains and substantial environmental benefits in the model.

4.3 Carbon Tax Shocks

To quantify the macroeconomic and environmental implications of Korea's decarbonization path, we evaluate the introduction of a permanent **5% tax on brown energy** (an increase from zero to 5 percent). The reform raises the price of brown energy faced by households and firms and therefore directly affects production costs, consumption choices, and the energy mix. Because brown energy is imported and paid for in foreign currency, the carbon tax amplifies the pass-through of exchange rate movements to domestic energy prices. We consider three distinct fiscal configurations that differ in how carbon-tax revenues are redistributed to the economy:

(i) **Case 1: Transfers to Hand-to-Mouth (HtM) households**. All carbon-tax revenues are rebated as lump-sum transfers exclusively to HtM households.

(ii) **Case 2: Subsidies for green-energy purchases**. Revenues are used to subsidize green-energy consumption by households and intermediate firms, lowering the relative price of green energy.

(iii) **Case 3: Price subsidy for green-energy producers**. The government subsidizes the output price of the domestic green-energy sector, effectively increasing the profitability of green-capital accumulation and expanding renewable energy supply.

Taken together, these three cases provide a transparent way to map different uses of carbon-tax revenues into the model. Case 1 corresponds to a "redistribution-first" design, in which revenues are directed toward liquidity-constrained households to shield vulnerable groups and support aggregate demand. Case 2 reflects a "demand-side green transition" objective, using revenues to lower the effective price of clean energy and accelerate substitution away from fossil fuels in consumption and production. Case 3 captures a "supply-side green industrial policy" motive, where revenues are used to raise the profitability of green-energy production and stimulate investment in renewable capacity. Comparing outcomes across these three regimes highlights how the same carbon tax can generate very different macroeconomic, distributional, and environmental consequences depending on how its revenues are redistributed.

Figure 14 compares the effects of a carbon-tax shock across the three revenue-use schemes described above. The top-left panel shows that the path of the carbon tax itself is identical in all cases:

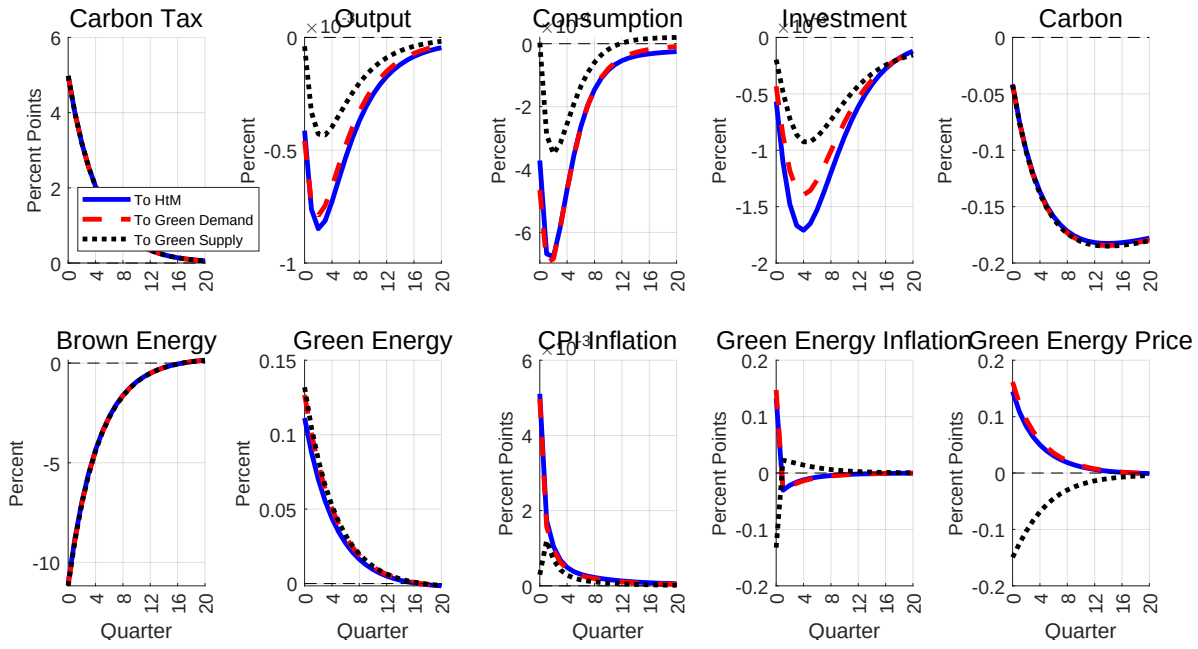


Figure 14: Responses of Key Aggregate Variables to a Carbon Tax Shock

Note: This figure shows impulse responses to a 5pp increase in the carbon tax under three alternative uses of carbon-tax revenues: transfers to HtM households (solid blue), subsidies to green-energy demand (red dashed), and subsidies to green-energy supply (black dotted). All variables are expressed as percent (or percentage-point) deviations from their steady state, and the horizontal axis denotes quarters after the shock.

the tax rate increases by about 5 percentage points on impact and then gradually decays. Because the tax path is the same, the initial contraction in aggregate activity is fairly similar across regimes, but the way revenues are used matters for the strength and persistence of the downturn.

In the output panel, all three cases display a short-run contraction following the carbon-tax shock, but the magnitude and persistence differ markedly across regimes. The downturn is strongest when revenues are rebated to HtM households (solid blue line) and weakest when they are used to support green-energy supply (dotted black line), with the green-demand subsidy (dashed red line) lying in between but closer to the first case. In both the HtM-transfer and green-demand-subsidy cases, the higher after-tax price of carbon-intensive energy lowers consumption through two channels. First, there is a direct channel: energy is complementary to consumption in the composite expenditure aggregator, so higher energy costs reduce effective consumption. Second, there is an indirect general-equilibrium channel: wages fall and the real interest rate rises, further depressing consumption. By contrast, when revenues are directed to green-energy producers, these two contractionary forces are partially offset by an additional mechanism: the subsidy stimulates green-energy production, lowers the relative price of green energy, increases green-energy use, and thereby mitigates the negative

impact of the carbon tax on consumption.

The environmental effects are much more similar across the three designs. In particular, the carbon stock responds almost identically in all three scenarios, because brown-energy use adjusts in a very similar way across them. This reflects the fact that, in the model, the carbon-tax rate itself is the primary driver of emissions; the way revenues are redistributed mainly shapes macroeconomic and price responses rather than the path of aggregate carbon. Green-energy use, however, is relatively sensitive to the revenue design. The supply-side subsidy produces the most favorable response for green energy. The HtM transfer scheme is least effective from this perspective: green-energy use increases less. The results also show how revenue design shapes prices and inflation within the energy block. CPI inflation rises modestly and temporarily in all three regimes, as the higher user cost of carbon-intensive energy makes carbon taxation inflationary on impact. However, the inflationary effect is smallest under the supply-side subsidy, because the policy lowers the price of green energy and reduces green-energy inflation, partially offsetting the rise in overall inflation.

For a given carbon-tax path, the way revenues are used has first-order consequences for the output cost and the inflation profile of the policy. All three schemes generate a short-run decline in GDP and a temporary rise in CPI inflation, reflecting higher effective prices of carbon-intensive energy. However, the size of the output loss is clearly smallest when revenues are directed to green-energy supply. The results suggest that if policymakers' main concern is to minimize the output cost of decarbonization while keeping inflation pressures contained, revenue designs that strengthen the supply side of the green-energy sector are preferable to pure transfer schemes.

5 Discussion

5.1 Role of Substitution Between Brown and Green Energy

A key parameter in the model is the elasticity of substitution between brown and green energy in the CES energy aggregator used by households and intermediate-goods firms. To gauge its quantitative importance, we recompute the impulse responses for three values of this elasticity: a low-substitution case ($\eta_E = 1.5$, black dotted line), the benchmark ($\eta_E = 2.3$, blue solid line), and a high-substitution

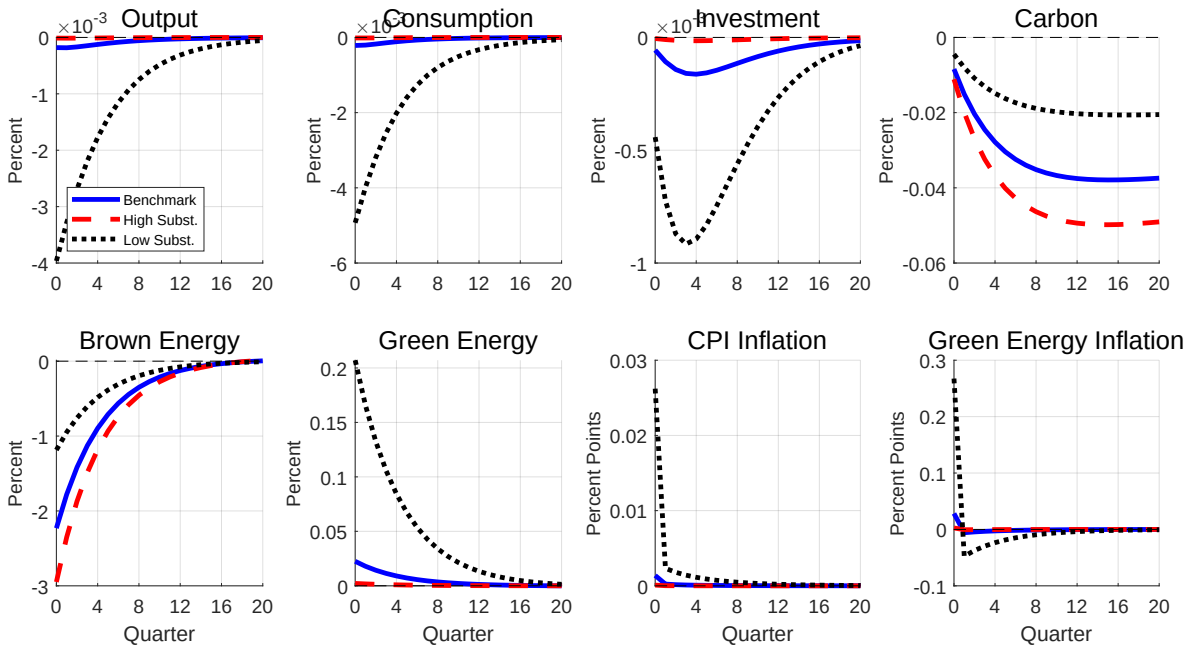


Figure 15: BROWN-ENERGY PRICE SHOCK WITH VARIOUS η_E

Note: The figure plots impulse responses to a one-time increase in the world price of brown energy under three values of the elasticity of substitution between brown and green energy, η_E. The black dotted line corresponds to the low-substitution case ($\eta_E = 1.5$), the blue solid line to the benchmark ($\eta_E = 2.3$), and the red dashed line to the high-substitution case ($\eta_E = 3.0$). All variables are expressed as percentage deviations from their steady state (inflation in percentage points), and the horizon is in quarters.

case ($\eta_E = 3.0$, red dashed line).[27] We focus on energy-related shocks: the figures report these three paths for each of the experiments considered—brown-energy price shocks, green-technology shocks, and carbon-tax shocks.[28]

Figure 15 illustrates how this elasticity shapes the transmission of a brown-energy price shock. In the top row, output, consumption, and investment all fall on impact. With high substitutability, the economy mainly responds through reallocation: firms substitute strongly from brown to green energy, so emissions and the carbon stock fall a lot, while the macro downturn and inflation are relatively mild. When substitutability is low, the reallocation margin is weak and the higher brown-energy price shows up as a larger increase in the cost of the energy bundle, generating a deeper recession and a bigger CPI-inflation spike but a smaller reduction in brown use and carbon. At the same time, because green demand is less price-elastic in this case, the shift toward green energy produces a larger increase in both its price and its quantity.

Figure 16 reports the responses to a positive green-technology shock. The expansion is modest but

[27] Since Berthold et al. (2023) use $\eta_E = 1.5$, while Nakov and Thomas (2023) consider higher values around $\eta_E = 3.0$, we treat these two values as lower and upper bounds for the parameter.

[28] For the remaining shocks, such as TFP and UIP disturbances, see the Appendix.

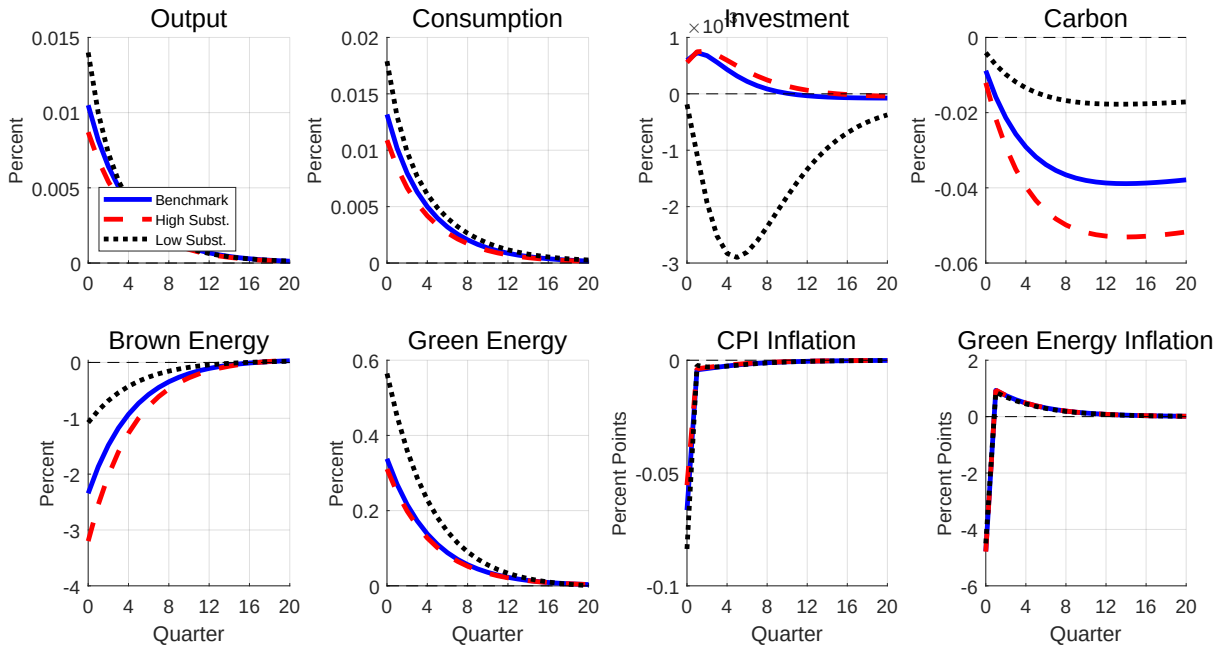


Figure 16: Green-technology Shocks with Various η_E

Note: The figure plots impulse responses to a one-time increase in green technology under three values of the elasticity of substitution between brown and green energy, η_E. The black dotted line corresponds to the low-substitution case ($\eta_E = 1.5$), the blue solid line to the benchmark ($\eta_E = 2.3$), and the red dashed line to the high-substitution case ($\eta_E = 3.0$). All variables are expressed as percentage deviations from their steady state (inflation in percentage points), and the horizon is in quarters.

clearly stronger when brown and green energy are less substitutable: the low-substitution case yields the largest in output and consumption, while the high-substitution calibration delivers the weakest response. The carbon stock falls in all three cases as cheaper green energy reduces the overall emissions; the decline is strongest under high substitution. The shock is disinflationary: CPI inflation falls on impact in all cases, with the largest decline under low substitution, as cheaper green energy more strongly lowers firms' marginal costs. Green-energy inflation shows a sharp negative spike.

Overall, a green-technology improvement is pro-growth and pro-environment in all calibrations, but lower substitutability between brown and green energy amplifies the macro expansion, because a given fall in the effective cost of the energy composite has a larger impact on marginal costs when energy is more complementary to other inputs. The increase in green-energy use is also larger in the low-substitution case, as the stronger expansion in output raises total energy demand more, even though the change in the brown–green energy mix is smaller.

Figure 17 displays the responses to an increase in the carbon tax on brown energy with revenues rebated to hand-to-mouth household. The top row shows that output, consumption, and investment all decline on impact. The size of this contraction is strongly decreasing in η_E: in the low-substitution

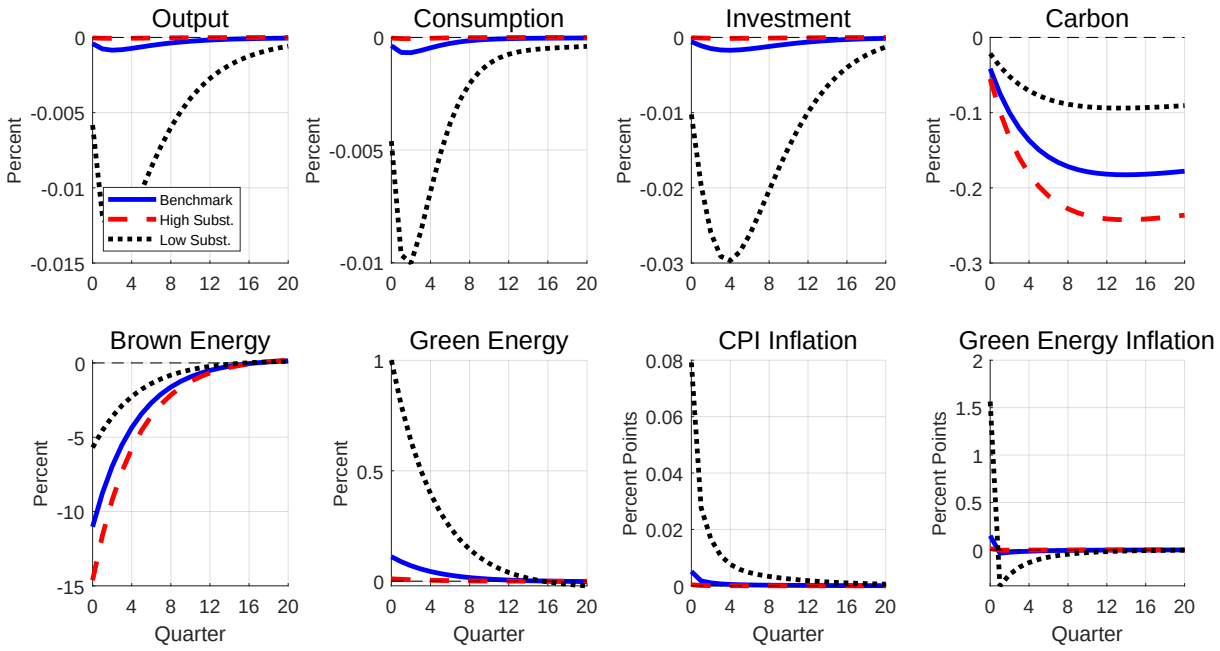


Figure 17: Carbon-tax Shocks with Various η_E

Note: The figure plots impulse responses to a one-time increase in carbon tax rates under three values of the elasticity of substitution between brown and green energy, η_E. The black dotted line corresponds to the low-substitution case ($\eta_E = 1.5$), the blue solid line to the benchmark ($\eta_E = 2.3$), and the red dashed line to the high-substitution case ($\eta_E = 3.0$). All variables are expressed as percentage deviations from their steady state (inflation in percentage points), and the horizon is in quarters.

economy, the carbon tax acts like a sizable adverse supply shock, generating a persistent fall in real activity, whereas under the high-substitution calibration the recessionary effects are very small. The carbon stock declines in all three cases because emissions fall, with the largest and most persistent reduction under high substitution, where the tax leads to a large drop in total energy use. The mechanism is similar to the brown-energy price shock. When substitutability is low, the reallocation margin is weak and the higher brown-energy price shows up as a larger increase in the cost of the energy bundle, generating a deeper recession and a bigger CPI-inflation spike but a smaller reduction in brown use and carbon.

Taken together, the three experiments underscore that the elasticity of substitution between brown and green energy, η_E, is a central parameter for both the macroeconomic and environmental implications of energy and climate shocks. A low η_E makes the economy fragile to disturbances in brown-energy prices and carbon taxation: shocks then operate primarily as adverse supply shocks, generating sizable and persistent declines in output and investment, stronger inflationary pressures in the case of taxes or price hikes, and large but recession-driven reductions in emissions. By contrast, when η_E is high, households and firms can reallocate more easily toward green energy, so brown-energy price

and carbon-tax shocks have much smaller effects on real activity and inflation, but they also deliver more modest cuts in the carbon stock. For green-technology improvements, a higher η_E amplifies the expansionary effects by facilitating substitution into cheaper green energy, raising output while still lowering emissions. Hence, the degree of substitutability between brown and green energy governs the fundamental trade-off between macroeconomic stabilization and climate mitigation in our small open economy.

5.2 Distributional Effects

The model features two household groups: (i) optimizing households, who can save and borrow subject to standard budget constraints and thus smooth consumption intertemporally, and (ii) hand-to-mouth households, who have no access to financial assets and consume their current disposable income each period. Since our model features two types of households, it is also interesting to examine how macroeconomic shocks affect consumption for each type. Hence, in this subsection, we discuss the distributional effects across household types, focusing on consumption dynamics.

5.2.1 Carbon Tax

We first examine the distributional effects of the carbon-tax adoption experiment, in which the government introduces a permanent 5-percentage-point tax on brown energy starting from an initial rate of zero. We then analyze whether these distributional effects differ across the three revenue-neutral reallocation schemes: (i) lump-sum transfers to HtM households, (ii) subsidies to green-energy purchases by households and intermediate firms, and (iii) a price subsidy to green-energy producers. Each panel shows aggregate, optimizing, and HtM consumption under the three schemes.

Figure 18 plots the consumption responses of total, optimizing, and hand-to-mouth (HtM) households to a carbon-tax shock under the three revenue-use schemes. At the aggregate level (left panel), the carbon tax is mildly contractionary in all cases: total consumption falls on impact and then gradually returns toward steady state. The magnitude of the decline, however, differs across schemes. The decline is smallest when revenues are used to support green-energy supply (black dotted line), whereas the other two scenarios generate very similar aggregate consumption responses.

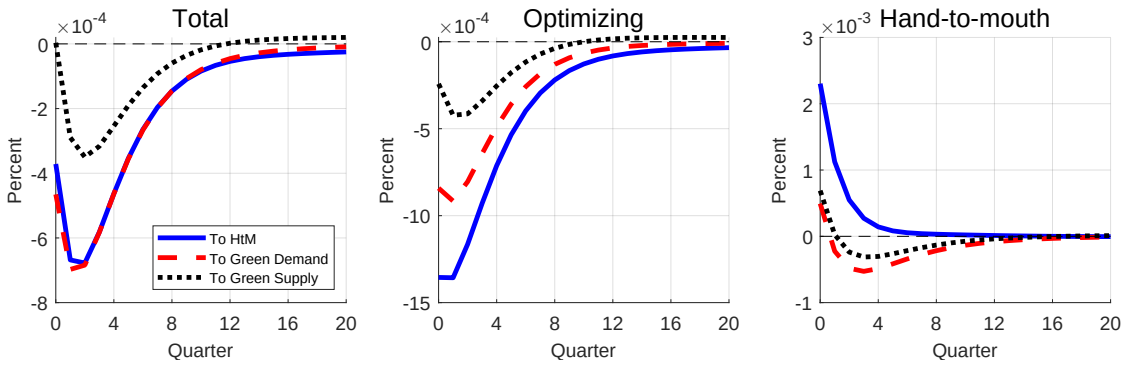


Figure 18: Consumption Responses by Household Type to Carbon-tax Shocks

Note: Impulse responses of consumption to a carbon-tax shock under three revenue–use schemes: transfers to HtM households (solid blue), subsidies to green-energy demand (red dashed), and subsidies to green-energy supply (black dotted). The left panel shows aggregate consumption, the middle panel shows consumption of optimizing (Ricardian) households, and the right panel shows consumption of hand-to-mouth households.

In the HtM-transfer case, optimizing (Ricardian) households reduce consumption, with the decline being strongest among the three scenarios, whereas HtM workers' consumption increases the most in this regime. Intuitively, the higher carbon tax compresses dividend income of the intermediate firm and raises the real interest rate, both of which depress Ricardian households' consumption. By contrast, HtM consumption rises because the additional transfer is targeted exclusively to HtM households. Thus, if we interpret HtM workers as poorer households in the cross-section, this scheme reduces consumption inequality significantly.

Under the price subsidy to green-energy producers, households can purchase green energy at a lower relative price and substitute it for brown energy. This attenuates the negative impact of the carbon tax on the effective cost of energy services and implies that Ricardian consumption falls the least among the three schemes. In addition, the subsidy boosts profits in the green-energy sector, raising dividend income and thereby supporting consumption—directly for Ricardian households and indirectly for HtM households through higher fiscal revenues available for transfers. So, HtM workers' consumption also increases.

By contrast, in the case of subsidies to green-energy purchases (the demand subsidy), the energy-substitution effect is still present, but there is no corresponding increase in dividends from the green-energy sector. As a result, optimizing households reduce consumption, and HtM workers' consumption falls the most in this regime.

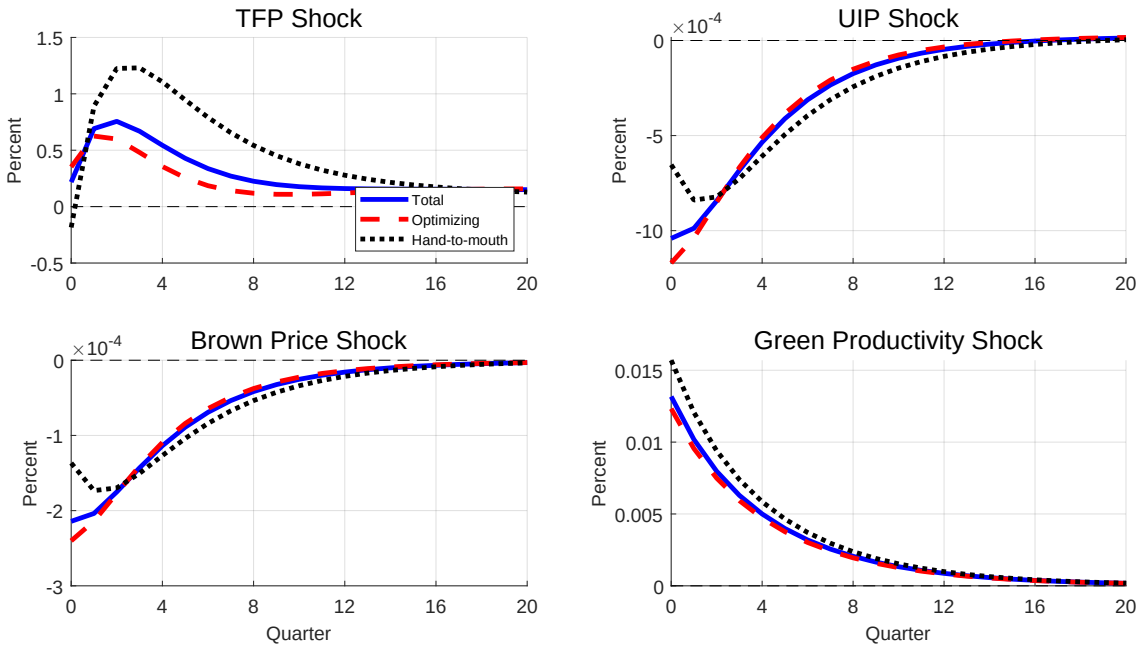


Figure 19: Consumption Responses by Household Type to Macro and Energy Shocks

Note: The figure plots impulse responses of total consumption (blue solid), optimizing (Ricardian) households' consumption (red dashed), and hand-to-mouth households' consumption (black dotted) to a one–standard-deviation TFP shock, UIP (risk-premium) shock, brown-energy price shock, and green-productivity shock. All series are shown as percent deviations from the non-stochastic steady state, with the horizon in quarters.

5.2.2 Macro and Energy Shocks

We next examines how other macro and energy-related shocks affect consumption inequality. Figure 19 reports the percentage deviations of aggregate, optimizing, and HtM consumption for four shocks—TFP, UIP, brown-energy price, and green-productivity shocks.

For a TFP shock, the model delivers a clearly progressive short-run pattern. In the upper-left panel of Figure 19, consumption rises for both groups, but the increase for HtM households (black dotted line) is much larger and more front-loaded than for optimizing households (red dashed line). Higher productivity raises labor demand and real wages on impact, and because HtM households consume all of their current income, the wage gain immediately shows up as a sharp jump in their consumption. By contrast, optimizing households smooth the associated income gain over time by allocating part of it to higher capital accumulation in response to the higher return. As a result, their consumption response is more gradual and substantially smaller than that of HtM workers.

By contrast, the UIP (risk-premium) shock and the brown-energy price shock are close to distributionally neutral. In both cases, consumption declines for both optimizing and HtM households. The

key mechanism operates through higher brown-energy prices: as shown in Figures 6 and 10, both shocks raise the brown-energy price. The brown-energy price shock does so directly, whereas the UIP shock increases it indirectly via an exchange-rate change. Given the complementarity between energy and non-durable consumption, households reduce both energy demand and non-durable consumption.[29] It is also worth noting that, in the very short run, the consumption decline is somewhat larger for optimizing households than for HtM households. These shocks raise the return on capital, which induces optimizing households to cut consumption more sharply in order to increase savings (Figures 6 and 10).

Finally, the green-productivity shock (lower-right panel) is clearly progressive. An improvement in green-sector technology lowers the price of green energy and stimulates its use, so both household types gain, but HtM consumption rises by more and earlier than optimizing households' consumption. HtM households benefit directly from higher real wages, which translate one-for-one into current consumption. Optimizing households, in contrast, allocate part of the windfall to additional asset accumulation, so their consumption response is more muted.

In sum, productivity and green-technology shocks are both pro-growth and clearly pro-poor: HtM households gain disproportionately because higher wages and cheaper green energy translate directly into current spending. By contrast, the UIP (risk-premium) shock and the brown-energy price shock are approximately distributionally neutral. Thus, whether a shock or policy is "good" or "bad" for the aggregate economy is only part of the story; its incidence across optimizing and liquidity-constrained households can differ sharply, which is central for evaluating energy and climate policies in an unequal economy.

6 Monetary Policy Implications

Monetary policy in the model follows a Taylor-type rule in which the nominal interest rate responds to deviations of CPI inflation from target and to the output gap as well as nominal exchange rates. To study how this rule interacts with climate and energy dynamics, we conduct a sensitivity analysis

[29] This limited distributional impact partly reflects our calibration: we assume the energy–non-energy substitution elasticity and the energy expenditure share are identical across household types. If these parameters differ across optimizing and HtM households, stronger distributional effects would likely emerge.

with respect to these coefficients.[30]

6.1 Output Stabilization

We first compare a benchmark calibration with an intermediate output weight to a more aggressive rule ("High Y", $\phi_Y = 0.50$) and to a purely inflation-targeting rule with no output stabilization ("Low Y", $\phi_Y = 0.0$). In all experiments, the inflation coefficient is kept fixed, so differences across simulations reflect only how strongly the central bank stabilizes real activity. To keep the discussion focused, we report responses of key aggregate variables to the three energy-related shocks considered above—brown-energy price shocks, green-technology shocks, and carbon-tax shocks.[31]

A positive brown-energy price shock behaves like a standard imported oil-price shock: it raises production costs, reduces real activity, and generates inflationary pressure. In all three policy rules, output and consumption fall on impact, while CPI inflation increases (Figure 20). The Low-Y rule (black dotted line), which does not respond to the output gap, allows the deepest and most persistent decline in output. The resulting weakness in demand also mutes price pressures, so the CPI inflation response is smallest under this rule. As ϕ_Y is raised, the central bank leans more aggressively against the recession. Under the High-Y rule (red dashed line), output, consumption, and investment fall much less, but the stabilization of real activity comes at the cost of a larger and more persistent increase in CPI inflation. The benchmark rule (blue line) lies between these two cases. Thus, in the face of adverse fossil-fuel price shocks, a larger weight on the output gap mitigates the depth of the slump but amplifies the inflation overshoot, making the output–inflation trade-off explicit. The environmental implications of the brown-energy price shock remain only of second order. Across all three policy rules, brown-energy use falls sharply and the carbon stock declines gradually, with only negligible differences across regimes. The paths of atmospheric carbon are almost indistinguishable. Also, the response of green energy is not sensitive to monetary policy.

A green-technology shock raises productivity in the green-energy sector and is both expansionary and disinflationary. Output, consumption, and investment all increase on impact, while CPI inflation falls as cheaper green energy reduces firms' marginal costs (Figure 21). The strength of the

[30] In the main text, we focus on output and inflation stabilization. For the analysis of exchange-rate stabilization, see the Appendix.

[31] Responses to TFP and UIP shocks are provided in the Appendix.

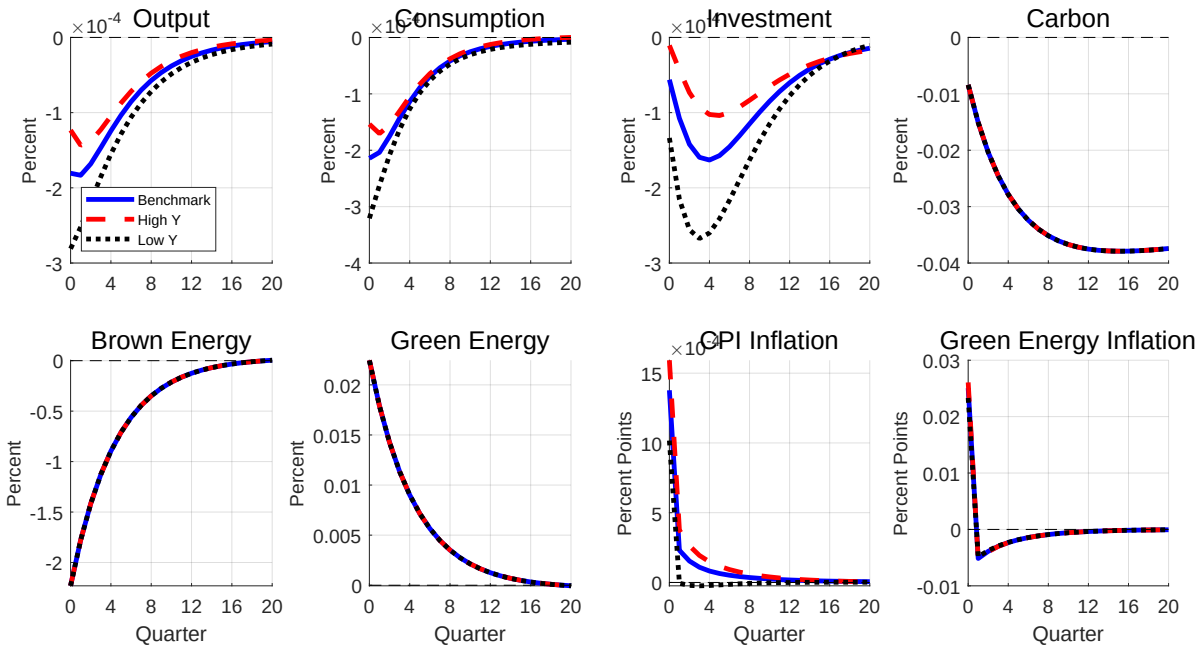


Figure 20: Output Stabilization and brown-energy price Shock

Note: Impulse responses to a one-time increase in the international price of brown energy under three monetary-policy rules: benchmark Taylor rule (solid blue), high output-gap weight ("High Y", red dashed), and zero output-gap weight ("Low Y", black dotted). Panels show output, consumption, investment, atmospheric carbon, brown- and green-energy use, CPI inflation, and green-energy inflation. All series are in percent (or percentage-point) deviations from steady state; the horizontal axis denotes quarters after the shock.

boom, however, depends on the output-gap weight. Under the Low-Y rule, the central bank largely accommodates the positive demand effect: output and investment rise the most and inflation falls the least. The High-Y rule reacts more aggressively to the expansion, raising the policy rate by more and thereby dampening the increase in activity; at the same time, it delivers a somewhat stronger disinflation. The benchmark rule again lies in between. In other words, when green-technology progress arrives, a larger ϕ_Y mainly serves to smooth the business-cycle amplitude of the "green boom," rather than to change its sign. The environmental consequences of the brown-energy price shock are only of secondary importance.

The carbon-tax adoption experiment—an increase in the brown-energy tax from 0 to 5 percent with revenues rebated to hand-to-mouth households—is the case where the choice of ϕ_Y has especially clear policy relevance (Figure 22). In all three rules, the higher tax acts like a cost-push disturbance: output, consumption, and investment fall, and CPI inflation rises as the user cost of fossil energy increases. Under the Low-Y rule, the central bank is relatively passive in the face of the contraction, allowing a sizable and persistent decline in GDP and the largest, most sustained increase in inflation. Raising the output-gap weight markedly improves this trade-off. Under the High-Y rule,

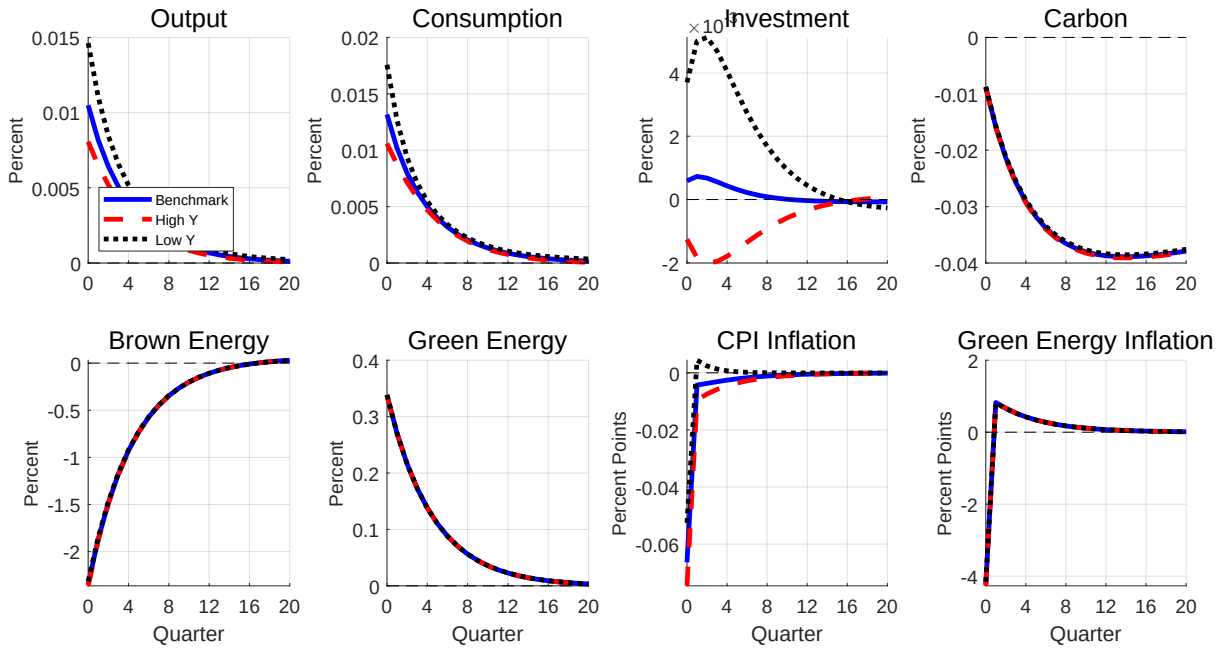


Figure 21: Output Stabilization and Green-Technology Shock

Note: Impulse responses to a 1-percent improvement in green-energy productivity under three monetary-policy rules: benchmark Taylor rule (solid blue), high output-gap weight ("High Y", red dashed), and zero output-gap weight ("Low Y", black dotted). Panels show output, consumption, investment, atmospheric carbon, brown- and green-energy use, CPI inflation, and green-energy inflation. All series are in percent (or percentage-point) deviations from steady state; the horizontal axis denotes quarters after the shock.

the fall in output and consumption is smallest, investment recovers more quickly, and the inflation response is most contained. The benchmark rule again lies between these extremes. As with the other shocks, the environmental outcome—reduced brown-energy use and a lower carbon stock—is very similar across policy rules.

6.2 Inflation Stabilization

In this experiment, monetary policy differs only in the inflation coefficient of the Taylor rule. We compare a benchmark rule with $\phi_\pi = 1.5$ to a more aggressive inflation-targeting rule ("High Infl.", $\phi_\pi = 2.0$) and a less aggressive rule ("Low Infl.", $\phi_\pi = 1.25$). The weight on the output gap is held fixed, so differences across simulations isolate how strongly the central bank stabilizes inflation.

A positive brown-energy price shock acts as an imported cost-push disturbance: it raises production costs, reduces real activity, and generates inflationary pressure. In all three rules, output, consumption, and investment fall on impact, while CPI inflation increases (Figure 23). A stronger inflation response improves price stability but slightly worsens the real downturn. The High-Inflation

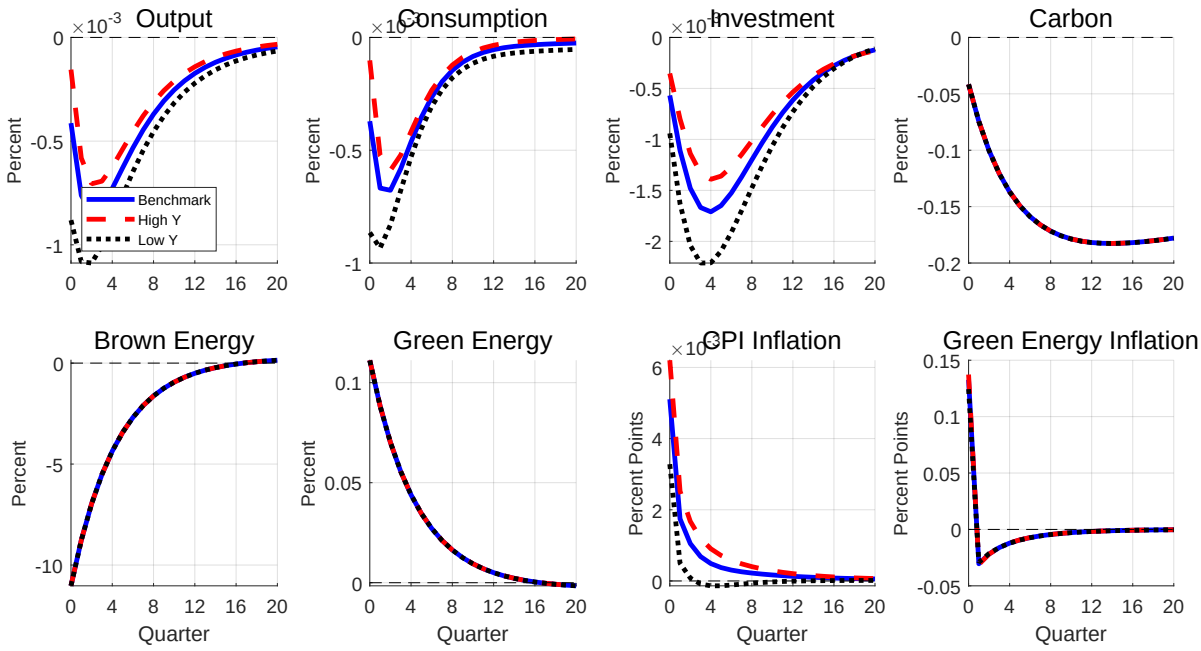


Figure 22: Output Stabilization and Carbon Tax Shock

Note: Impulse responses to an increase in the carbon tax rate from 0 to 5 percent, with revenues rebated to hand-to-mouth households, under the benchmark, High-Y, and Low-Y Taylor rules (solid blue, red dashed, and black dotted, respectively). Panels display output, consumption, investment, atmospheric carbon, brown- and green-energy use, CPI inflation, and green-energy inflation, in percent deviations from steady state.

rule generates the smallest and shortest-lived rise in CPI inflation, but also the deepest and most persistent fall in investment and a somewhat larger decline in output compared with the benchmark. The Low-Inflation rule tolerates a bigger and more persistent inflation response, while cushioning the contraction in activity. Energy quantities and the carbon stock move almost identically across rules; brown-energy use falls and carbon declines gradually, indicating that the choice of ϕ_π mainly reallocates the burden between output and inflation without materially altering emissions.

For a green-technology shock, which raises productivity in the green-energy sector and is intrinsically disinflationary (Figure 24). The High-Inflation rule cuts the policy rate most aggressively when inflation falls below target, delivering the largest increases in output and investment and the smallest decline in CPI inflation. Under the Low-Inflation rule, the central bank reacts only weakly to the disinflation; the boom in activity is more muted and CPI inflation falls the most. The environmental effects—higher green-energy use, lower brown-energy use, and a decline in carbon—are very similar across rules, with only minor quantitative differences.

As mention above, an increase in the brown-energy tax behaves like a persistent cost-push shock (Figure 25). In all regimes, output, consumption, and investment fall and CPI inflation rises. With

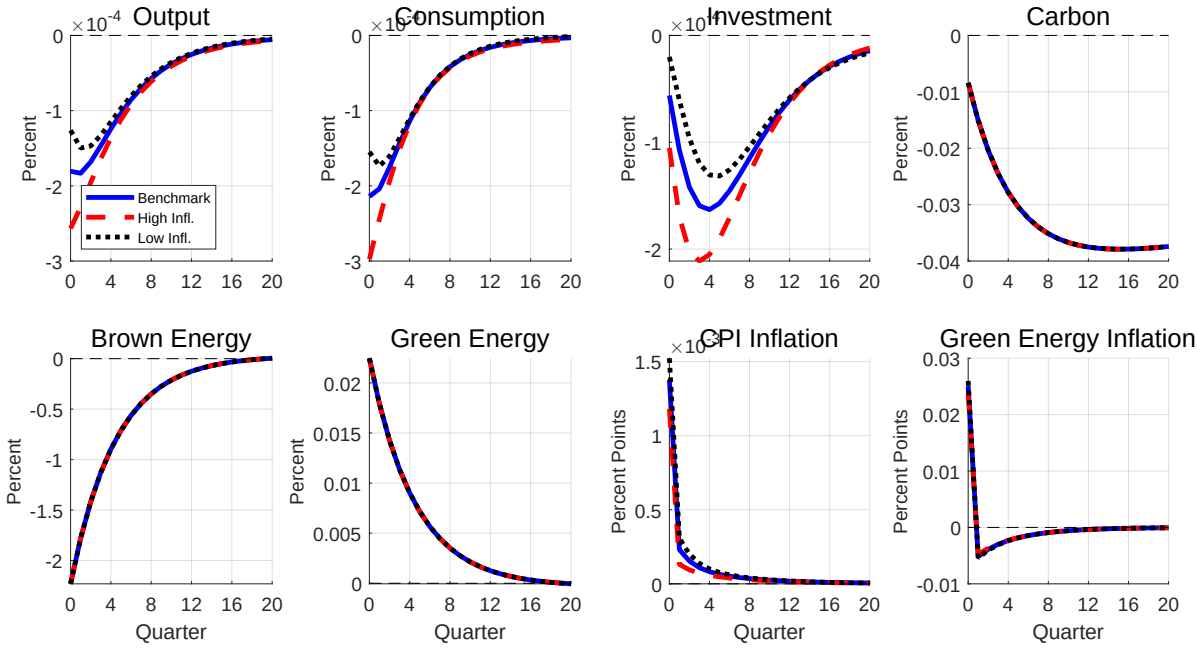


Figure 23: Inflation Stabilization and brown-energy price Shock

Note: Impulse responses to a one-time increase in the international price of brown energy under three Taylor rules: Benchmark (blue), High Inflation response (red), and Low Inflation response (black). All variables are shown as percent (or percentage-point) deviations from steady state
Panels show output, consumption, investment, atmospheric carbon, brown- and green-energy use, CPI inflation, and green-energy inflation. All series are in percent (or percentage-point) deviations from steady state; the horizontal axis denotes quarters after the shock.

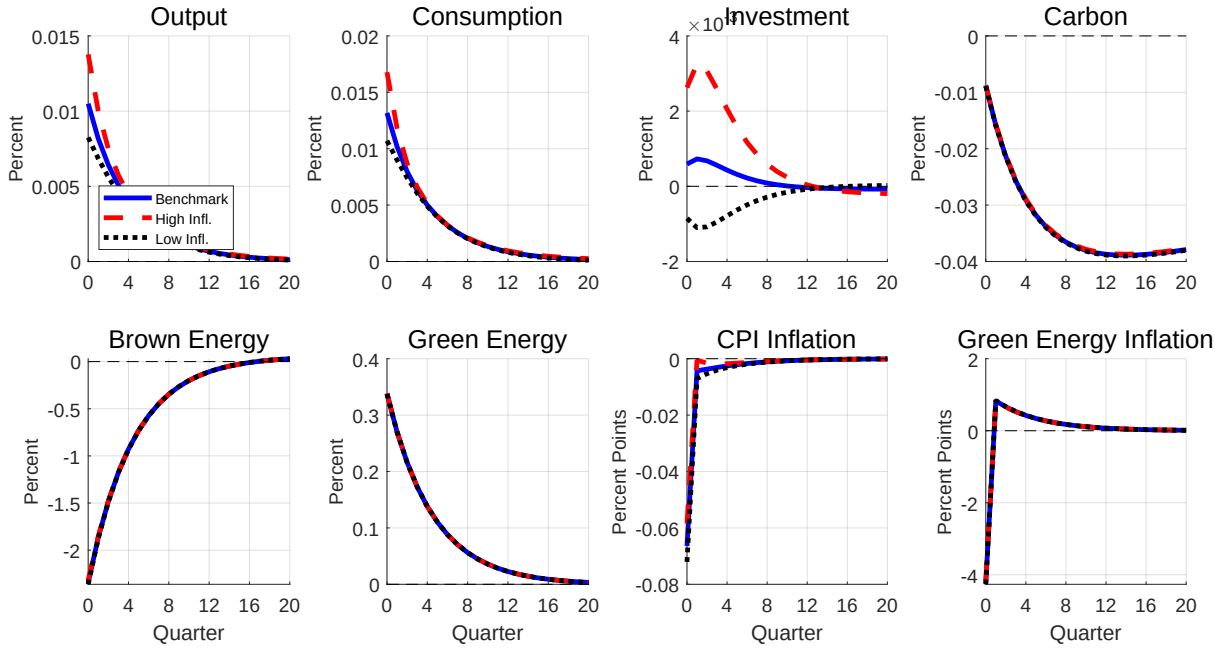


Figure 24: Inflation Stabilization and Green-Technology Shock

Note: Impulse responses to a 1-percent improvement in green-energy productivity under three Taylor rules: Benchmark (blue), High Inflation response (red), and Low Inflation response (black). Panels show output, consumption, investment, atmospheric carbon, brown- and green-energy use, CPI inflation, and green-energy inflation. All series are in percent (or percentage-point) deviations from steady state; the horizontal axis denotes quarters after the shock.

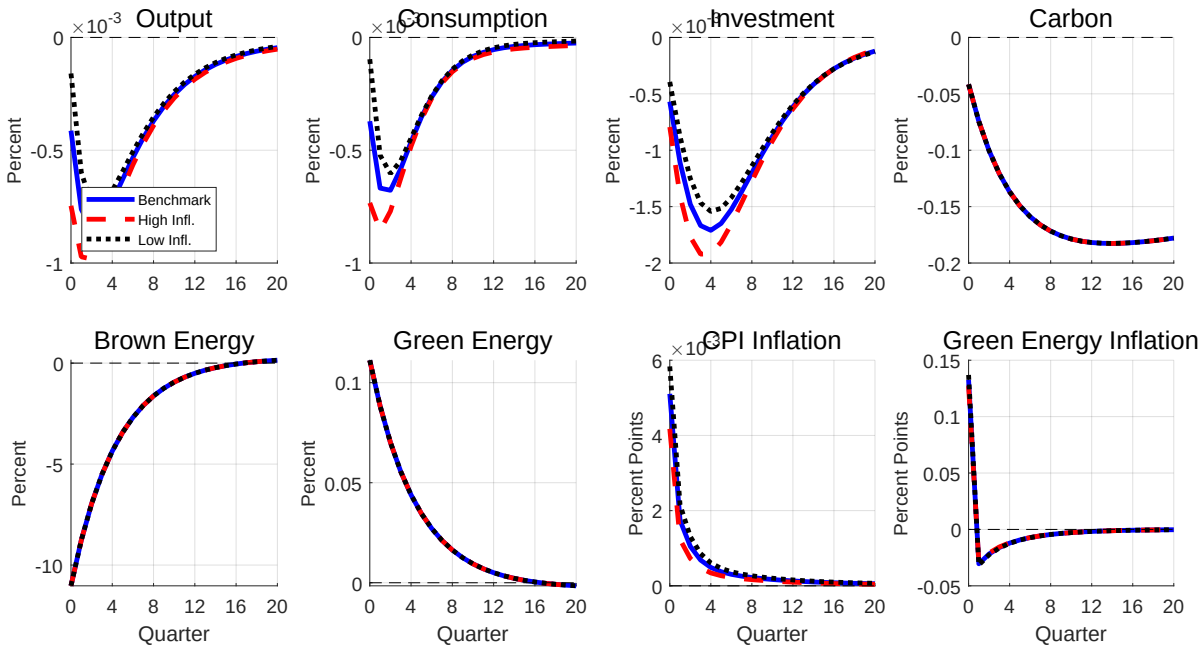


Figure 25: Inflation Stabilization and Carbon Tax Shock

Note: Impulse responses to an increase in the carbon tax rate from 0 to 5 percent under three Taylor rules: Benchmark (blue), High Inflation response (red), and Low Inflation response (black).. Panels display output, consumption, investment, atmospheric carbon, brown- and green-energy use, CPI inflation, and green-energy inflation, in percent deviations from steady state.

a higher ϕ_π, the central bank stabilizes inflation more forcefully: the High-Inflation rule produces the smallest and least persistent increase in CPI inflation, but at the cost of slightly larger and more protracted output and investment losses. The Low-Inflation rule accepts a bigger and more persistent inflation response while cushioning the real side somewhat. As in the other experiments, brown-energy use and atmospheric carbon fall by very similar amounts regardless of ϕ_π, so the environmental impact of the carbon tax is virtually invariant to the degree of inflation stabilization, whereas the output cost is not.

To conclude, monetary policy in this model primarily redistributes the burden of energy and climate shocks between output and inflation; it has only second-order effects on emissions and atmospheric carbon. In other words, Taylor-rule coefficients matter a lot for business-cycle stabilization around a given climate policy, but they are not an effective instrument for materially changing environmental outcomes.

7 Conclusion

This paper develops a DSGE model of a small open economy that imports fossil-based brown energy and produces renewable green energy domestically, tailored to key features of Korea. By combining a two-source energy block, climate damages, open-economy financial frictions, and the coexistence of Ricardian and hand-to-mouth households, the model provides a unified framework to study how external shocks, carbon pricing, and macroeconomic policy jointly shape output, inflation, the energy mix, and emissions.

The quantitative analysis delivers four main results. First, once the energy and open-economy blocks are taken seriously, different shocks generate sharply distinct macro–climate profiles. TFP and green-technology shocks are expansionary and disinflationary, whereas UIP (risk-premium) shocks and brown-energy price shocks are stagflationary but strongly carbon-reducing.

Second, the model reveals rich distributional effects that depend on the nature of shocks. Whether a shock or policy is "good" or "bad" for the aggregate economy is only part of the story; its incidence across optimizing and liquidity-constrained households can differ sharply, which is central for evaluating energy and climate policies in an unequal economy.

Third, monetary policy in this framework primarily redistributes the burden of energy and climate shocks between output and inflation, with only second-order effects on emissions and atmospheric carbon.

Finally, two structural features are pivotal. The degree of substitutability between brown and green energy governs the strength of the trade-off between real activity and environmental improvement. In addition, for a given carbon-tax path, the way revenues are redistributed has first-order consequences for the output cost and inflation profile of the policy. Hence, for small, energy-importing economies like Korea, effective decarbonization requires not just the right carbon price, but also careful design of revenue use and support for green substitutability.

The analysis can be extended in several directions. Incorporating richer sectoral heterogeneity in production, explicit investment in energy efficiency, and more detailed financial frictions would allow for a more granular assessment of firm-level and distributional impacts. On the policy side, the framework could be used to study a broader set of monetary arrangements—including "green

QE" and alternative policy mixes between monetary, fiscal, and climate instruments—as well as an extended trade structure with explicit exports and imports of goods in addition to energy.

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Appendix

A System of Equations: Benchmark Economy

$$X_t^s = \left((1-\psi_E^s)^{\frac{1}{\eta^s}} \left(C_t^s\right)^{\frac{\eta^s-1}{\eta^s}} + \psi_E^{s\,\frac{1}{\eta^s}} \left(E_t^s\right)^{\frac{\eta^s-1}{\eta^s}} \right)^{\frac{\eta^s}{\eta^s-1}} \tag{A.1}$$

$$E_t^s = \left(\psi_{E_B}^{s\,\frac{1}{\eta_E^s}} \left(E_{B,t}^s\right)^{\frac{\eta_E^s-1}{\eta_E^s}} + \left(1-\psi_{E_B}^s\right)^{\frac{1}{\eta_E^s}} \left(E_{G,t}^s\right)^{\frac{\eta_E^s-1}{\eta_E^s}} \right)^{\frac{\eta_E^s}{\eta_E^s-1}} \tag{A.2}$$

$$K_t^s = (1-\delta) K_{t-1}^s + \left(1 - \frac{\phi_I}{2} \left(\frac{I_t^s}{I_{t-1}^s} - 1 \right)^2 \right) I_t^s \tag{A.3}$$

$$\left(X_t^s\right)^{-\sigma} - \mu_{X,t}^s = 0 \tag{A.4}$$

$$\mu_{X,t}^s \left(X_t^s\right)^{\frac{1}{\eta^s}} (1-\psi_E^s)^{\frac{1}{\eta^s}} \left(C_t^s\right)^{-\frac{1}{\eta^s}} - \lambda_t^s p_{Y,t} = 0 \tag{A.5}$$

$$\mu_{X,t}^s \left(X_t^s\right)^{\frac{1}{\eta^s}} \psi_E^{s\,\frac{1}{\eta^s}} \left(E_t^s\right)^{-\frac{1}{\eta^s}} - \mu_{E,t}^s = 0 \tag{A.6}$$

$$\mu_{E,t}^s \left(E_t^s\right)^{\frac{1}{\eta_E^s}} \psi_{E_B}^{s\,\frac{1}{\eta_E^s}} \left(E_{B,t}^s\right)^{-\frac{1}{\eta_E^s}} - \lambda_t^s (1+\tau_t^c) p_{E_B,t} = 0 \tag{A.7}$$

$$\mu_{E,t}^s \left(E_t^s\right)^{\frac{1}{\eta_E^s}} \left(1-\psi_{E_B}^s\right)^{\frac{1}{\eta_E^s}} \left(E_{G,t}^s\right)^{-\frac{1}{\eta_E^s}} - \lambda_t^s (1-tr_t^c) p_{E_G,t} = 0 \tag{A.8}$$

$$-\chi^s \left(N_t^s\right)^{\varphi} + \lambda_t^s w_t = 0 \tag{A.9}$$

$$-\lambda_t^s p_{Y,t} + \mu_{K,t}^s \left(1 - \frac{\phi_I}{2} \left(\frac{I_t^s}{I_{t-1}^s} - 1 \right)^2 - \phi_I \left(\frac{I_t^s}{I_{t-1}^s} - 1 \right) \frac{I_t^s}{I_{t-1}^s} \right) + \beta \phi_I \mathbb{E}_t \mu_{K,t+1}^s \left(\frac{I_{t+1}^s}{I_t^s} - 1 \right) \left(\frac{I_{t+1}^s}{I_t^s} \right)^2 = 0 \tag{A.10}$$

$$-\mu_{K,t}^s + \beta \mathbb{E}_t \left(\lambda_{t+1}^s r_{t+1}^k + \mu_{K,t+1}^s (1-\delta) \right) = 0 \tag{A.11}$$

$$-\lambda_t^s + \beta \mathbb{E}_t \lambda_{t+1}^s \frac{R_t}{\pi_{t+1}} = 0 \tag{A.12}$$

$$-\lambda_t^s \left(1 + \phi_B \left(b_t^{s*} - b^{s*}\right)\right) + \beta \mathbb{E}_t \lambda_{t+1}^s \frac{R^*}{\pi^*} \frac{\mathcal{Q}_{t+1}}{\mathcal{Q}_t} = 0 \tag{A.13}$$

$$X_t^h = \left(\left(1-\psi_E^h\right)^{\frac{1}{\eta^h}} \left(C_t^h\right)^{\frac{\eta^h-1}{\eta^h}} + \psi_E^{h\,\frac{1}{\eta^h}} \left(E_t^h\right)^{\frac{\eta^h-1}{\eta^h}} \right)^{\frac{\eta^h}{\eta^h-1}} \tag{A.14}$$

$$E_t^h = \left({\psi_{E_B}^h}^{\frac{1}{\eta_E^h}} \left(E_{B,t}^h\right)^{\frac{\eta_E^h - 1}{\eta_E^h}} + \left(1 - \psi_{E_B}^h\right)^{\frac{1}{\eta_E^h}} \left(E_{G,t}^h\right)^{\frac{\eta_E^h - 1}{\eta_E^h}} \right)^{\frac{\eta_E^h}{\eta_E^h - 1}} \tag{A.15}$$

$$p_{Y,t} C_t^h + (1 + \tau_t^c) p_{E_B,t} E_{B,t}^h + (1 - tr_t^c) p_{E_G,t} E_{G,t}^h = w_t N_t^h + T_t^h \tag{A.16}$$

$$\left(X_t^h\right)^{-\sigma} - \mu_{X,t}^h = 0 \tag{A.17}$$

$$\mu_{X,t}^h \left(X_t^h\right)^{\frac{1}{\eta^h}} \left(1 - \psi_E^s\right)^{\frac{1}{\eta^h}} \left(C_t^h\right)^{-\frac{1}{\eta^h}} - \lambda_t^h p_{Y,t} = 0 \tag{A.18}$$

$$\mu_{X,t}^h \left(X_t^h\right)^{\frac{1}{\eta^h}} {\psi_E^s}^{\frac{1}{\eta^h}} \left(E_t^h\right)^{-\frac{1}{\eta^h}} - \mu_{E,t}^h = 0 \tag{A.19}$$

$$\mu_{E,t}^h \left(E_t^h\right)^{\frac{1}{\eta_E^h}} {\psi_{E_B}^s}^{\frac{1}{\eta_E^h}} \left(E_{B,t}^h\right)^{-\frac{1}{\eta_E^h}} - \lambda_t^h (1 + \tau_t^c) p_{E_B,t} = 0 \tag{A.20}$$

$$\mu_{E,t}^h \left(E_t^h\right)^{\frac{1}{\eta_E^h}} \left(1 - \psi_{E_B}^s\right)^{\frac{1}{\eta_E^h}} \left(E_{G,t}^h\right)^{-\frac{1}{\eta_E^h}} - \lambda_t^h (1 - tr_t^c) p_{E_G,t} = 0 \tag{A.21}$$

$$-\chi^h \left(N_t^h\right)^{\varphi} + \lambda_t^h w_t = 0 \tag{A.22}$$

$$\Delta_t Y_t = \widetilde{A}_t \left((1 - \alpha_E)^{\frac{1}{\zeta}} \left(\left(K_t^y\right)^{\alpha_K} \left(N_t^y\right)^{1 - \alpha_K} \right)^{\frac{\zeta - 1}{\zeta}} + {\alpha_E}^{\frac{1}{\zeta}} \left(E_t^y\right)^{\frac{\zeta - 1}{\zeta}} \right)^{\frac{\zeta}{\zeta - 1}} \tag{A.23}$$

$$\Delta_t = (1 - \theta) \left(\frac{p_{Y,t}^*}{p_{Y,t}} \right)^{-\varepsilon} + \theta \left(\frac{p_{Y,t}}{p_{Y,t-1}} \frac{\pi_t}{\pi} \right)^{\varepsilon} \Delta_{t-1} \tag{A.24}$$

$$E_t^y = \left({\alpha_{E_B}}^{\frac{1}{\zeta_E}} \left(E_{B,t}^y\right)^{\frac{\zeta_E - 1}{\zeta_E}} + \left(1 - \alpha_{E_B}\right)^{\frac{1}{\zeta_E}} \left(E_{G,t}^y\right)^{\frac{\zeta_E - 1}{\zeta_E}} \right)^{\frac{\zeta_E}{\zeta_E - 1}} \tag{A.25}$$

$$\frac{r_t^k K_t^y}{Y_t} - \alpha_K \left(1 - \alpha_E\right)^{\frac{1}{\zeta}} mc_t \widetilde{A}_t \left(\frac{\left(K_t^y\right)^{\alpha_K} \left(N_t^y\right)^{1 - \alpha_K}}{Y_t} \right)^{\frac{\zeta - 1}{\zeta}} = 0 \tag{A.26}$$

$$\frac{w_t N_t^y}{Y_t} - \left(1 - \alpha_K\right) \left(1 - \alpha_E\right)^{\frac{1}{\zeta}} mc_t \widetilde{A}_t \left(\frac{\left(K_t^y\right)^{\alpha_K} \left(N_t^y\right)^{1 - \alpha_K}}{Y_t} \right)^{\frac{\zeta - 1}{\zeta}} = 0 \tag{A.27}$$

$$-{\alpha_E}^{\frac{1}{\zeta}} mc_t \widetilde{A}_t \left(\frac{E_t^y}{Y_t} \right)^{\frac{\zeta - 1}{\zeta}} + \mu_{Y,t} \frac{E_t^y}{Y_t} = 0 \tag{A.28}$$

$$(1 + \tau_t^c) p_{E_B,t} - \mu_{Y,t} \left(E_t^y\right)^{\frac{1}{\zeta_E}} {\alpha_{E_B}}^{\frac{1}{\zeta_E}} \left(E_{B,t}^y\right)^{-\frac{1}{\zeta_E}} = 0 \tag{A.29}$$

$$(1 - tr_t^c) p_{E_G,t} - \mu_{Y,t} \left(E_t^y\right)^{\frac{1}{\zeta_E}} \left(1 - \alpha_{E_B}\right)^{\frac{1}{\zeta_E}} \left(E_{G,t}^y\right)^{-\frac{1}{\zeta_E}} = 0 \tag{A.30}$$

$$\frac{p_{Y,t}^*}{p_{Y,t}} = \frac{\varepsilon}{\varepsilon - 1} \frac{CC_t}{BB_t} \tag{A.31}$$

$$CC_t = \lambda_t^s mc_t Y_t + \theta\beta^s \mathbb{E}_t(\frac{\pi_{Y,t+1}}{\pi})^{\varepsilon} CC_{t+1} \tag{A.32}$$

$$BB_t = \lambda_t^s p_{Y,t} Y_t + \theta\beta^s \mathbb{E}_t(\frac{\pi_{Y,t+1}}{\pi})^{\varepsilon-1} BB_{t+1} \tag{A.33}$$

$$(p_{Y,t})^{1-\varepsilon} = (1-\theta)\,(p_{Y,t}^*)^{1-\varepsilon} + \theta(p_{Y,t-1}\frac{\pi}{\pi_t})^{1-\varepsilon} \tag{A.34}$$

$$div_{Y,t} = p_{Y,t}Y_t - w_t N_t^y - r_t^k K_t^y - (1+\tau_t^c)p_{E_B,t}E_{B,t}^y - (1-tr_t^c)p_{E_G,t}E_{G,t}^y \tag{A.35}$$

$$p_{E_B,t} = \mathcal{Q}_t p_{E_B,t}^* \tag{A.36}$$

$$p_{E_B,t}^* = (1-\rho_B)\,p_{E_B}^* + \rho_B p_{E_B,t-1}^* + \sigma_B \varepsilon_{B,t} \tag{A.37}$$

$$E_{G,t} = A_{G,t}(K_t^e)^{\alpha_G} \tag{A.38}$$

$$div_{E,t} = p_{E_G,t}E_{G,t} - r_t^k K_t^e \tag{A.39}$$

$$\alpha_G p_{E_G,t} A_{G,t}(K_t^e)^{\alpha_G - 1} - r_t^k = 0 \tag{A.40}$$

$$S_t = (1-\vartheta)\,S_{t-1} + \vartheta_0\left(\lambda E_{B,t}^h + (1-\lambda)\,E_{B,t}^s + E_{B,t}^y\right) \tag{A.41}$$

$$1 - D_t(S_t) = \exp(-\omega(S_t - \bar{S})) \tag{A.42}$$

$$\widetilde{A}_t = [1 - D_t(S_t)]\,A_t \tag{A.43}$$

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\rho_R}\left(\left(\frac{\pi_t}{\pi}\right)^{\phi_\pi}\left(\frac{Y_t}{Y}\right)^{\phi_Y}\left(\frac{\mathcal{E}_t}{\mathcal{E}_{t-1}}\right)^{\phi_E}\right)^{1-\rho_R} \tag{A.44}$$

$$\frac{\mathcal{Q}_t}{\mathcal{Q}_{t-1}} = \frac{\mathcal{E}_t}{\mathcal{E}_{t-1}}\frac{\pi^*}{\pi_t} \tag{A.45}$$

$$1 = (p_t^s)^{1-\lambda}(p_t^h)^{\lambda} \tag{A.46}$$

$$p_t^s = \left((1-\psi_E^s)\,(p_{Y,t})^{1-\eta^s} + \psi_E^s(p_{E,t}^s)^{1-\eta^s}\right)^{\frac{1}{1-\eta^s}} \tag{A.47}$$

$$p_{E,t}^s = \left(\psi_{E_B}^s(p_{E_B,t})^{1-\eta_E^s} + \left(1-\psi_{E_B}^s\right)(p_{E_G,t})^{1-\eta_E^s}\right)^{\frac{1}{1-\eta_E^s}} \tag{A.48}$$

$$p_t^h = \left(\left(1-\psi_E^h\right)(p_{Y,t})^{1-\eta^h} + \psi_E^h(p_{E,t}^h)^{1-\eta^h}\right)^{\frac{1}{1-\eta^h}} \tag{A.49}$$

$$p^h_{E,t} = \left(\psi^h_{E_B}(p_{E_B,t})^{1-\eta^h_E} + \left(1-\psi^h_{E_B}\right)(p_{E_G,t})^{1-\eta^h_E}\right)^{\frac{1}{1-\eta^h_E}} \tag{A.50}$$

$$\pi_{Y,t} = \frac{p_{Y,t}}{p_{Y,t-1}}\pi_t \tag{A.51}$$

$$\lambda T^h_t = \tau_d\left(div_{Y,t} + div_{E,t}\right) \tag{A.52}$$

$$\tau^c_t p_{E_B,t} E_{B,t} = tr^c_t p_{E_G,t} E_{G,t} \tag{A.53}$$

$$Y_t = C_t + I_t \tag{A.54}$$

$$TB_t = (1-\lambda)\left(\mathcal{Q}_t b^{s*}_t - \mathcal{Q}_t \frac{R^*}{\pi^*} b^{s*}_{t-1} + \frac{\phi_B}{2}\mathcal{Q}_t\left(b^{s*}_t - b^{s*}\right)^2\right) \tag{A.55}$$

$$TB_t = -p_{E_B,t}\left(\lambda E^h_{B,t} + (1-\lambda)E^s_{B,t} + E^y_{B,t}\right) \tag{A.56}$$

$$C_t = \lambda C^h_t + (1-\lambda)C^s_t \tag{A.57}$$

$$I_t = (1-\lambda)I^s_t \tag{A.58}$$

$$K^y_t + K^e_t = (1-\lambda)K^s_{t-1} \tag{A.59}$$

$$E_{G,t} = \lambda E^h_{G,t} + (1-\lambda)E^s_{G,t} + E^y_{G,t} \tag{A.60}$$

$$E_{B,t} = \lambda E^b_{B,t} + (1-\lambda)E^s_{B,t} + E^y_{B,t} \tag{A.61}$$

$$N^y_t = \lambda N^h_t + (1-\lambda)N^s_t \tag{A.62}$$

B Other Results

B.1 Exchange Rate Stabilization

To highlight the small-open-economy dimension of the model, we augment the Taylor rule with a response to nominal exchange-rate movements. In the benchmark rule, $\phi_E = 0$, so monetary policy reacts only to inflation and the output gap. We then consider two alternative rules: a mild FX-

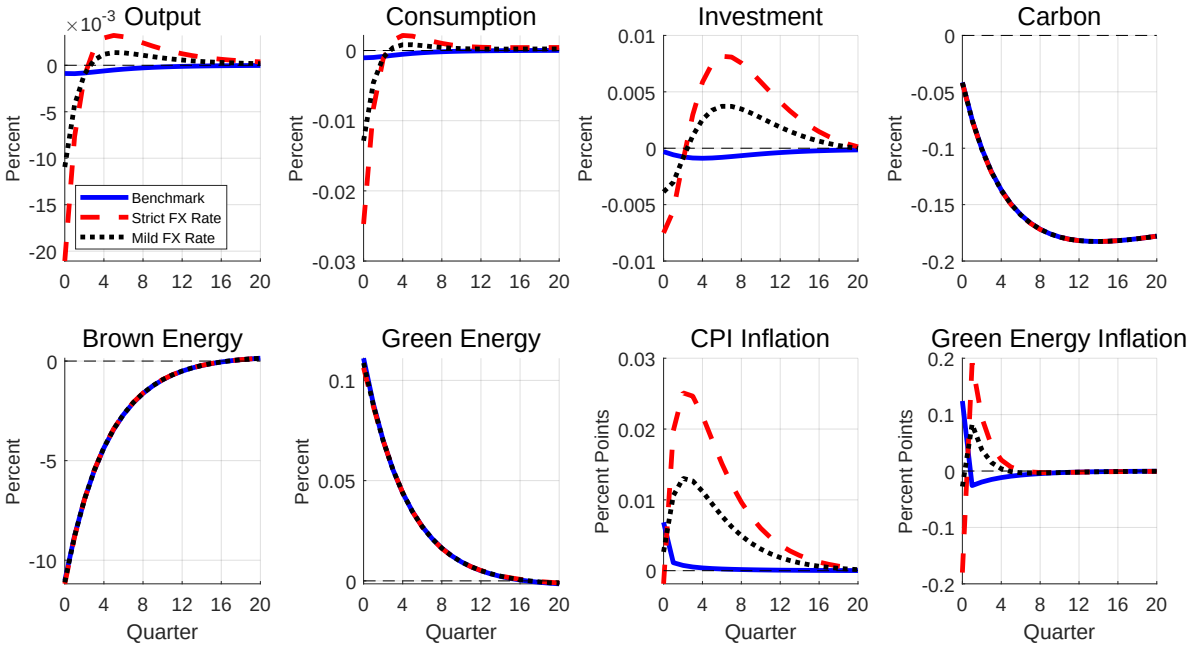


Figure A.1: Exchange Rate Stabilization and UIP Shock

Note: This figure shows impulse responses to a 1 percent UIP (risk-premium) shock under three monetary-policy rules that differ only in the strength of exchange-rate stabilization: the benchmark Taylor rule with no FX term (blue), a mild FX-stabilization rule ("Mild FX", black dotted), and a strict FX-stabilization rule ("Strict FX", red dashed, with a much larger coefficient on nominal depreciation).

stabilization rule ("Mild FX", black dotted line) with $\phi_E = 0.01$, and a strict FX-stabilization rule ("Strict FX", red dashed line) with $\phi_E = 0.02$. In both cases, the central bank raises the policy rate when the domestic currency depreciates and cuts it when the currency appreciates. In what follows we focus on UIP (risk-premium) shocks, for which the treatment of the exchange rate is most relevant.

Figure A.1 reports the responses of macro, energy, and climate variables to a 1-percent UIP (risk-premium) shock under three monetary-policy rules that differ only in the degree of exchange-rate stabilization. A positive UIP shock increases the country-specific risk premium and, in the absence of FX stabilization, tends to depreciate the currency and tighten financial conditions. Under the benchmark rule, the exchange rate is free to absorb most of the disturbance, so the macro contraction is quite mild: output and consumption fall only slightly, and investment moves little on impact. Once the central bank starts targeting the exchange rate, the adjustment mechanism changes dramatically. With mild FX stabilization, the policy rate is raised to resist the depreciation, which makes domestic real rates more volatile and amplifies the negative demand effect of the UIP shock. Output and consumption drop more on impact, and investment falls noticeably before recovering. Under the strict FX rule, this mechanism is much stronger: the central bank hikes rates aggressively to keep the

exchange rate from moving, so the UIP shock shows up mainly as a large domestic tightening.

The deeper recession under FX targeting also has important implications for prices and the energy block. Brown-energy use falls in all cases, but the differences across regimes are small. CPI inflation, by contrast, spikes under both FX-targeting rules—most under the strict rule—because the policy-rate hike and residual depreciation raise the domestic cost of energy and imported goods even as output contracts.

B.2 Damage Elasticity

We also conduct a sensitivity analysis with respect to the damage elasticity. Specifically, we compare the baseline calibration with two alternative cases: (i) no climate damages ($\omega = 0$) and (ii) a case in which the damage elasticity is increased by a factor of 100. The resulting impulse responses change little, both quantitatively and qualitatively (not shown in this paper). This suggests that, given our calibration, the damage elasticity is not a key parameter for the short- and medium-run dynamics emphasized in the paper.

B.3 Additional Figures

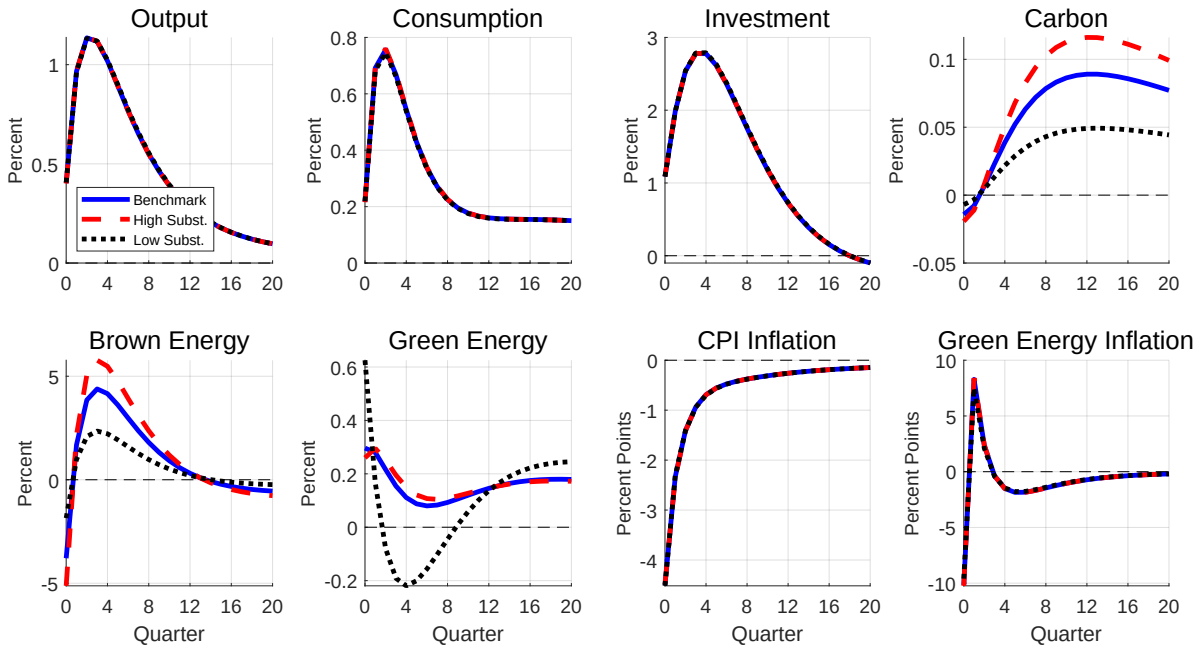


Figure A.2: TFP Shock with Various η_E

Note: The figure plots impulse responses under three values of the elasticity of substitution between brown and green energy, η_E. The black dotted line corresponds to the low-substitution case ($\eta_E = 1.5$), the blue solid line to the benchmark ($\eta_E = 2.3$), and the red dashed line to the high-substitution case ($\eta_E = 3.0$). All variables are expressed as percentage deviations from their steady state (inflation in percentage points), and the horizon is in quarters.

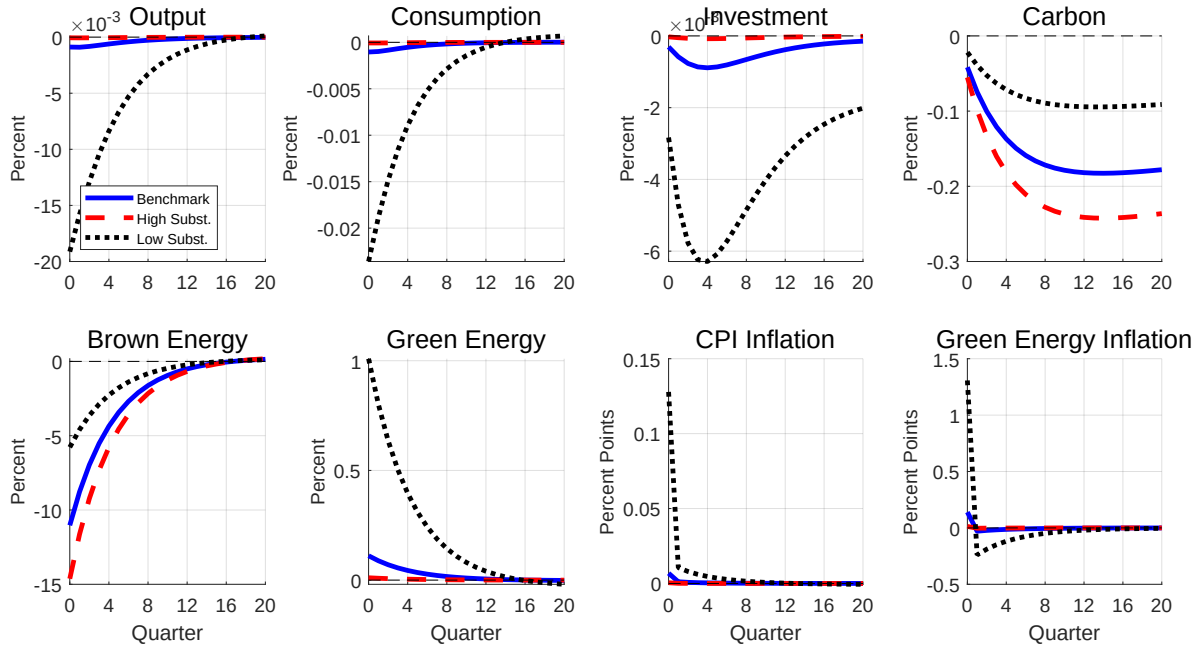


Figure A.3: UIP Shock with Various η_E

Note: The figure plots impulse responses under three values of the elasticity of substitution between brown and green energy, η_E. The black dotted line corresponds to the low-substitution case ($\eta_E = 1.5$), the blue solid line to the benchmark ($\eta_E = 2.3$), and the red dashed line to the high-substitution case ($\eta_E = 3.0$). All variables are expressed as percentage deviations from their steady state (inflation in percentage points), and the horizon is in quarters.

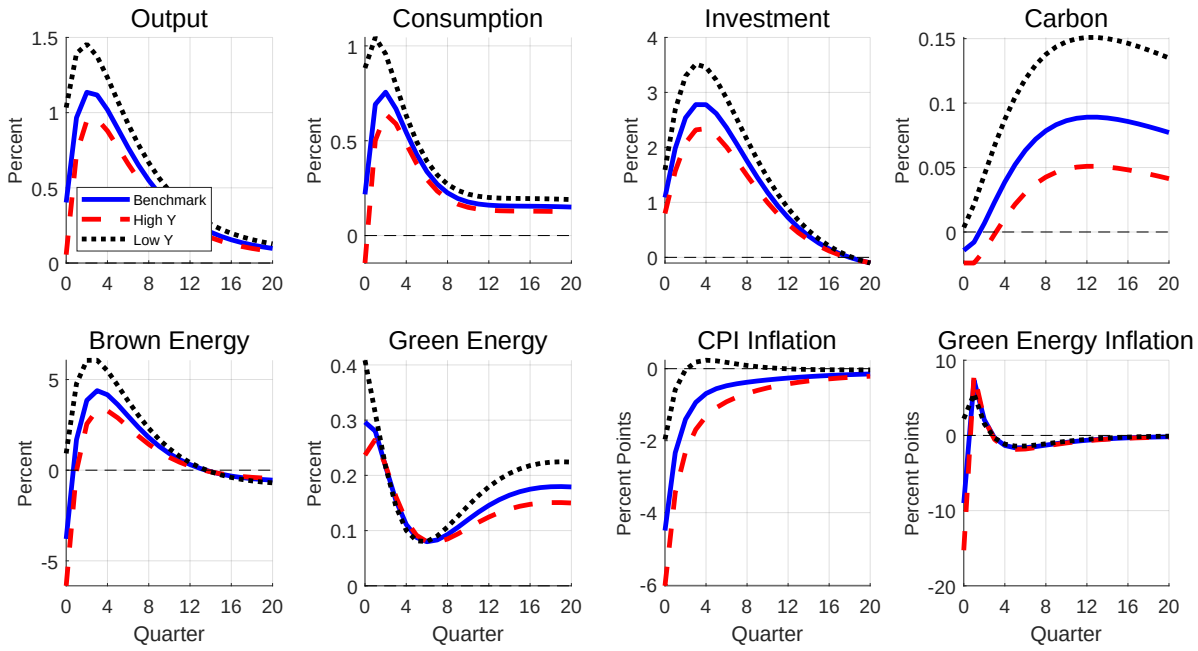


Figure A.4: Output Stabilization and TFP Shock

Note: Impulse responses under three monetary-policy rules: benchmark Taylor rule (solid blue), high output-gap weight ("High Y", red dashed), and zero output-gap weight ("Low Y", black dotted). Panels show output, consumption, investment, atmospheric carbon, brown- and green-energy use, CPI inflation, and green-energy inflation. All series are in percent (or percentage-point) deviations from steady state; the horizontal axis denotes quarters after the shock.

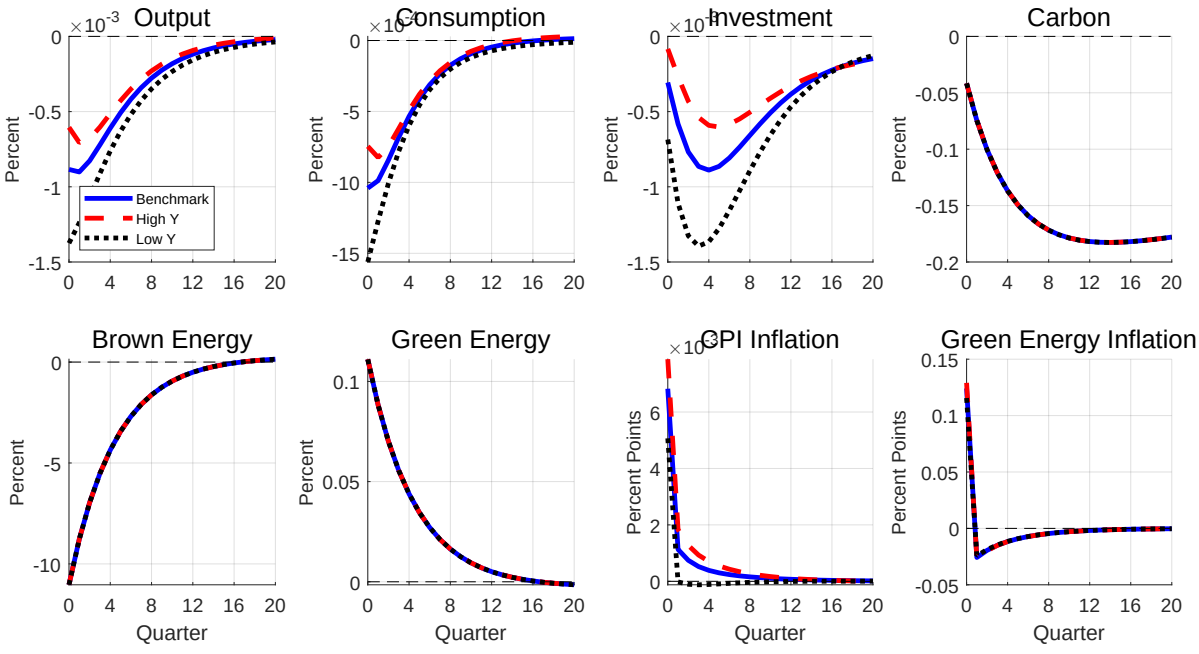


Figure A.5: Output Stabilization and UIP Shock

Note: Impulse responses under three monetary-policy rules: benchmark Taylor rule (solid blue), high output-gap weight ("High Y", red dashed), and zero output-gap weight ("Low Y", black dotted). Panels show output, consumption, investment, atmospheric carbon, brown- and green-energy use, CPI inflation, and green-energy inflation. All series are in percent (or percentage-point) deviations from steady state; the horizontal axis denotes quarters after the shock.

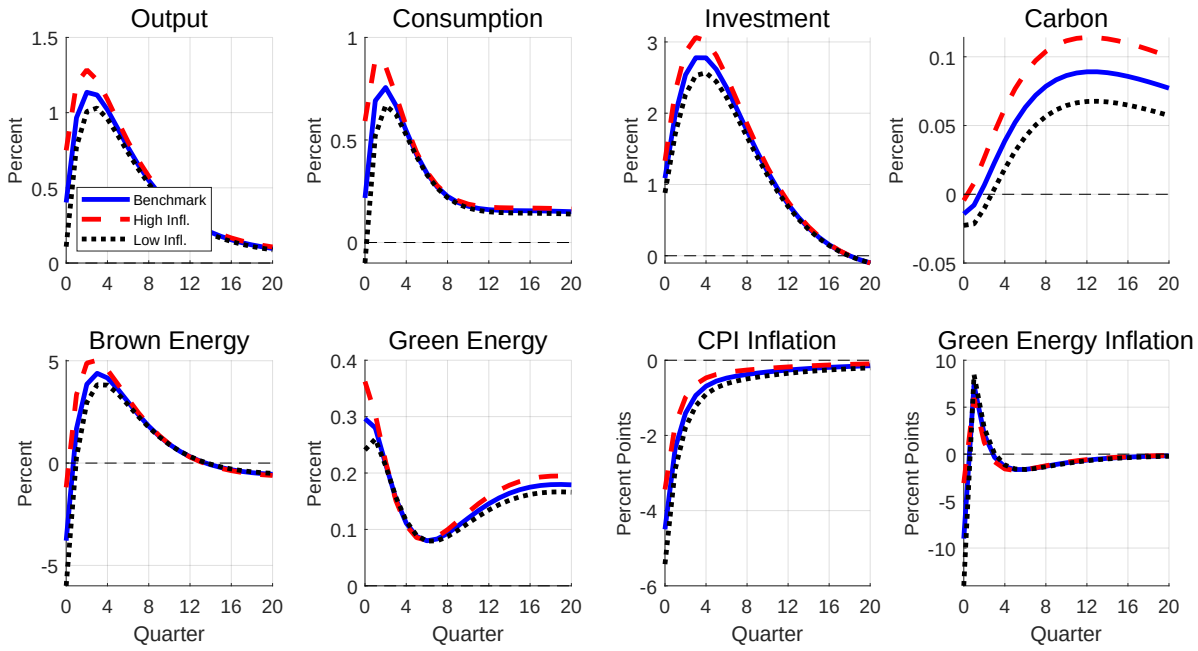


Figure A.6: Inflation Stabilization and TFP Shock

Note: Impulse responses under three monetary-policy rules: Benchmark (blue), High Inflation response (red), and Low Inflation response (black).. Panels display output, consumption, investment, atmospheric carbon, brown- and green-energy use, CPI inflation, and green-energy inflation, in percent deviations from steady state.

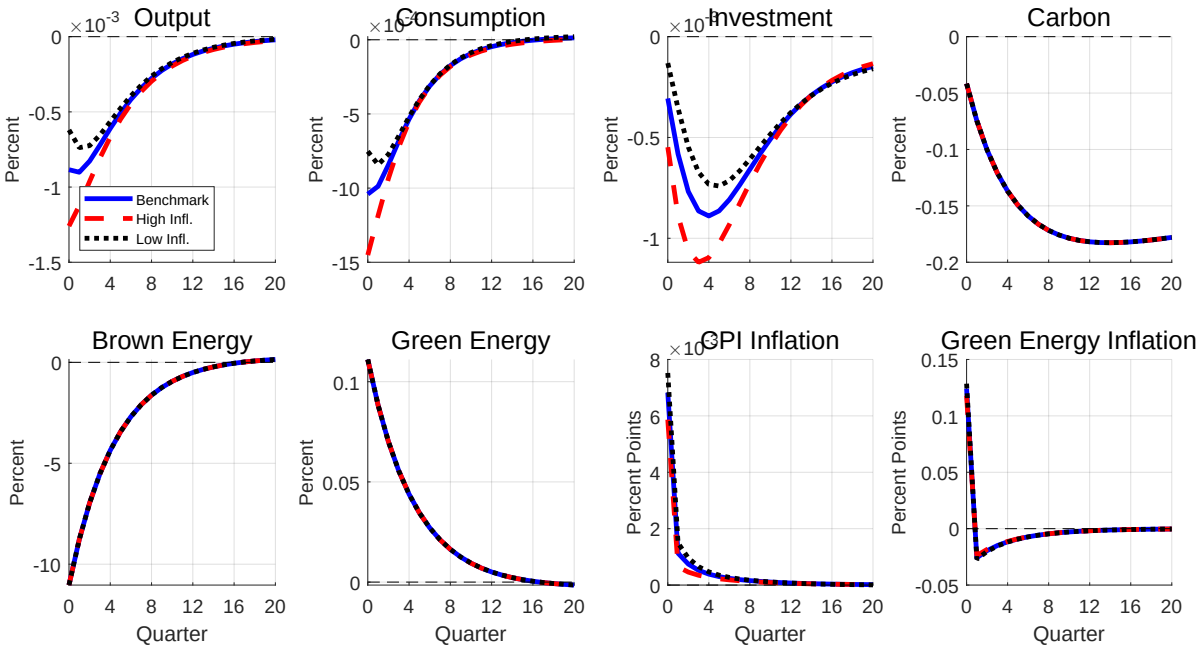


Figure A.7: Inflation Stabilization and UIP Shock

Note: Impulse responses under three monetary-policy rules: Benchmark (blue), High Inflation response (red), and Low Inflation response (black).. Panels display output, consumption, investment, atmospheric carbon, brown- and green-energy use, CPI inflation, and green-energy inflation, in percent deviations from steady state.