Italy's Green Transition: Evidence from an Estimated E-DSGE Model [*]

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Abstract

What does decarbonization cost Italy, who pays for it, and does the answer depend on how the revenues are used? This paper addresses these questions by means of an estimated open-economy environmental dynamic stochastic general equilibrium (E-DSGE) model with a detailed energy sector and liquidity-constrained households, fitted to Italian data over 1999Q1–2024Q4. Tightening the EU emissions caps for producers and households delivers the intended abatement, but at a persistent cost in output and consumption, borne disproportionately by liquidity-constrained households, who cannot smooth the loss of real income and whose baskets are somewhat more energy-intensive. A carbon border adjustment mechanism reverses this incidence, shifting the losses onto asset-owning households through the compression of firms' margins. In both cases aggregate welfare declines. What matters most, however, is how the revenues are used: the choice of recycling scheme shapes both the size and the distribution of the burden far more than the choice of instrument, and some schemes reverse it. Carbon pricing is regressive by default, not by necessity, but no single recycling scheme is both efficient and equitable.

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1 Introduction

Over the last two decades, the intensifying climate crisis has pushed environmental policy to the forefront of the EU economic agenda. The Fit for 55 package (European Commission, 2021) raised the 2030 emissions-reduction target to at least 55% below 1990 levels, a goal now enshrined in the European Climate Law, committing Member States to far-reaching reforms in energy, transport, and industry.[1] As the European Commission has put it, climate change and environmental degradation represent "an existential threat to Europe and the world" (European Commission, 2019).

The main instrument to reduce carbon emissions in the European Union is the Emissions Trading System (ETS), now covering roughly 35–40% of total EU greenhouse gas emissions (European Commission, 2023). With the Fit for 55 package, the EU expanded its carbon pricing architecture on two fronts. On the one hand, it introduced EU ETS 2, a separate cap-and-trade system dedicated to buildings, road transport, and small industrial installations, targeting sectors where carbon price signals are historically weak or fragmented.[2] On the other hand, it established the Carbon Border Adjustment Mechanism (CBAM), which extends carbon pricing to imports of selected carbon-intensive goods, aiming to limit carbon leakage and preserve the competitiveness of domestic producers subject to the ETS.[3] These climate policies considerably broaden the reach of European carbon pricing and, with it, the set of households and firms exposed to its costs.

Italy's transition path is particularly relevant from a policy perspective. The country remains one of the EU economies most dependent on imported energy, with an energy-dependency ratio of about 76% in 2023, which makes it highly exposed to fluctuations in global energy markets and to the effects of carbon pricing (see MASE 2024). Moving away from fossil fuels is thus not only a climate obligation but a way to reduce a long-standing external vulnerability. Moreover, in recent years, Italy has committed substantial resources to this transformation through the National Recovery and Resilience Plan (PNRR), which allocates more than 37% of its funds to green transition investments.[4]

Mitigation on this scale reshapes the structure of the economy, starting from the energy system: carbon pricing alters relative input costs and competitiveness, with

[1] See Regulation (EU) 2021/1119.

[2] EU ETS 2 was established under Directive (EU) 2023/959, with launch scheduled for 2028.

[3] CBAM was established under Regulation (EU) 2023/956 and entered its transitional phase in October 2023, with full implementation started in 2026. Early firm-level evidence suggests that the CBAM is already reshaping trade flows in covered sectors, reallocating EU-bound exports away from high-emission producers towards cleaner ones rather than acting as a uniform trade barrier (Vriz et al., 2026).

[4] Italy's PNRR allocates around €191.5 billion under the EU Recovery and Resilience Facility (Regulation (EU) 2021/241), complemented by €30 billion from national resources. It forms part of the EU's NextGenerationEU strategy introduced through Regulation (EU) 2020/2094.

repercussions for growth, employment, investment, and inflation (Pisani-Ferry, 2021; Ferriani et al., 2025). It also raises a question of incidence. Households differ in income, in the energy intensity of their consumption, and in their access to credit and clean technologies, so that the costs of the transition are unlikely to be evenly shared (Parry, 2015; Känzig, 2026; Nill et al., 2025). For Italy, where energy poverty is already significant and sensitive to price shocks this distributional dimension is not a secondary concern (Castellini et al., 2023; Aprea et al., 2024; Grazini, 2025).

In light of these challenges, this paper asks three questions. What does decarbonization cost the Italian economy? Who bears that cost? And how much of the answer to both depends on what the government does with the revenues? We address these questions using an updated and extended version of GEEM (General Equilibrium Environmental Model), a model tailored to the Italian economy and enriched with a detailed representation of the energy sector.[5] The model features a disaggregated energy block that distinguishes between fossil and renewable sources, explicitly linking energy use to emissions under EU ETS 1 (industry and power) and EU ETS 2 (transport and buildings). On the demand side, household heterogeneity is captured through the coexistence of two agents: optimizing households (Ricardian) and liquidity-constrained consumers (non-Ricardian), allowing the analysis to reflect differentiated responses to changes in energy and carbon prices. Standard nominal and real rigidities ensure realistic short-and medium-run adjustment dynamics. The key parameters are estimated using Bayesian techniques on quarterly Italian data over 1999Q1–2024Q4, allowing for time-varying volatility to accommodate the pandemic period.

Three results stand out. First, tightening the two ETS caps delivers the intended abatement at a persistent macroeconomic cost: after fifteen years, output is about 1.2% and consumption about 1.3% below baseline, and the burden is regressive. Liquidity-constrained households cut consumption by roughly twice as much as unconstrained ones, because they cannot smooth the income loss and their baskets are more energy-intensive. Second, the CBAM operates through an entirely different channel and reverses the incidence. Since it taxes imported intermediates rather than household energy, its (small) costs fall on asset-owning households through the compression of firms' margins, while liquidity-constrained households are largely spared. Third, and quantitatively most important, the use of the revenues matters more than the choice between instruments. Recycling through cuts in workers' social security contributions turns the welfare of liquidity-constrained households positive; recycling into renewable investment is the only scheme that raises aggregate welfare, yet it leaves the con-

[5] GEEM was originally developed for the Italian Ministry of Economy and Finance (Department of the Treasury), as a tool for macroeconomic and environmental policy analysis. In methodological terms, GEEM belongs to the class of environmental dynamic stochastic general equilibrium (E-DSGE) models. For an early version of GEEM, see Annicchiarico et al. (2017).

strained group no better off, because the returns accrue to the owners of clean capital. Carbon pricing, in short, is regressive by default but not by necessity, although no single recycling scheme delivers efficiency and equity at once.[6]

This paper contributes to the growing literature employing E-DSGE frameworks to assess the macroeconomic effects of climate and transition policies (Diluiso et al., 2021; Ferrari and Nispi Landi, 2024; Del Negro et al., 2023; Coenen et al., 2024; Dubois et al., 2025; Braga et al., 2025; Sahuc et al., 2025; Jondeau et al., 2026). Relative to this literature, the present analysis builds on GEEM, a large-scale open-economy E-DSGE model with a detailed energy sector, enabling a comprehensive assessment of how transition policies propagate through the Italian economy. In terms of analytical focus and modeling approach, the paper is closest to Varga et al. (2022), Bartocci et al. (2024), Ernst et al. (2023), Coenen et al. (2024), and Garcia et al. (2025). Relative to this literature, the contribution is threefold. First, the model is estimated rather than calibrated, using Bayesian methods over 1999Q1–2024Q4 with time-varying volatility to handle exceptional episodes such as the pandemic. Second, the framework embeds a detailed energy block with fossil and renewable sources alongside household heterogeneity, which is what allows the distributional incidence of ETS 2 and CBAM to be traced to observable differences in expenditure patterns, calibrated here on Italian micro data from the linked ISTAT–INPS Administrative Household Budget Survey (AD-HBS). Third, to the best of our knowledge, this is the first estimated E-DSGE assessment of a coordinated ETS–CBAM package, with revenue recycling, for the Italian economy.

The remainder of the paper is structured as follows. Section 2 describes the model. Section 3 reports the calibration and estimation results. Section 4 presents and discusses the policy scenarios, and Section 5 examines alternative uses of the carbon revenues. Section 6 concludes.

2 The Model

This section presents the revised version of GEEM, a large-scale New Keynesian model developed for the Italian economy and used as a policy laboratory to assess the macroeconomic impact of climate and energy policies. The model combines a wide range of nominal and real frictions, which shape short- and medium-run dynamics, with neoclassical mechanisms that dominate in the long run. It is designed to capture the transition dynamics triggered by carbon pricing under the EU Emissions Trading System and by a carbon border adjustment mechanism, and to this end embeds detailed

[6] For an extensive discussion of this point see also European Commission (2025) where the distributional impact on households (including several recycling schemes) of the ETS system has been presented using the E-QUEST model as described in Varga et al. (2022).

energy and environmental blocks suitable for simulation-based policy evaluation. For ease of exposition, this section presents only the objective functions, constraints, and technologies defining the model economy.

2.1 A Sketch of GEEM

GEEM comprises three regions: Italy (the domestic economy), the rest of the Euro Area (EA), and the rest of the world (RoW). The domestic economy is modeled in detail, whereas foreign economies are represented as stylized satellite economies that capture external demand and trade linkages (RoW), and the transmission of common policies (EA), namely sharing the monetary policy conducted by the European Central Bank (ECB) and participating in the EU ETS. Figure 1 represents the main blocks of the model, linking the Italian economy to the rest of Euro Area and the rest of the world.[7]

On the production side, monopolistically competitive firms produce a continuum of differentiated intermediate goods, combining labor and capital into value added and then value added with energy inputs (fossil and electricity) to obtain output. Perfectly competitive firms aggregate domestic and imported intermediate goods into final non-tradable output used for consumption, investments and public consumption. Monopolistically competitive energy producers supply electricity, distinguishing between fossil-based generation and renewable energy sources (RES). Importers purchase coal, crude oil, and natural gas for the electricity sector, foreign intermediate goods for the final-good sector, and fuel, gas, and electricity for household consumption. Exporting firms transform domestic intermediate goods into exportable products using a linear technology. Importing and exporting firms operate under monopolistic competition.

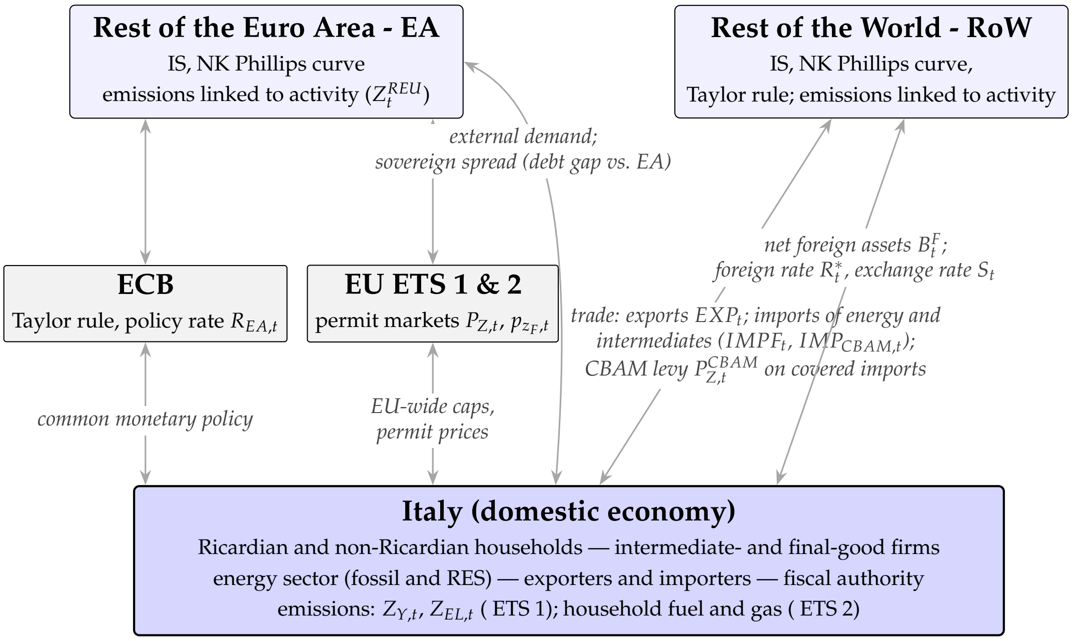
On the demand side, the economy is populated by two types of households that differ in their access to financial markets. Both consume final goods and energy, and supply labor to intermediate-good producers. The public sector comprises a national fiscal authority and a central bank which conducts monetary policy for the entire currency union.

Pollutant emissions in the domestic economy arise from different sources: production of intermediate goods, fossil-based electricity generation, and household use of refined oil and gas for heating and transport. The first two fall under EU ETS 1, the latter two under EU ETS 2, so that the two carbon-pricing regimes map directly onto distinct sets of emitters.

Finally, the EA and RoW blocks are each described by a standard three-equation New Keynesian structure: an IS, derived from a consumption Euler equation, a New

[7] For simplicity, we do not distinguish between the Euro Area and the European Union: the ETS and CBAM caps and permit prices are treated as common to the single non-domestic European block, which we label the Euro Area throughout.

Figure 1: Regional Structure of GEEM and Main Transmission Channels



Notes: The dark box is the fully specified domestic economy; light boxes are the two stylized satellite regions; grey boxes are the institutions shared with the rest of the Euro Area. Double-headed arrows denote the main transmission channels. Italy shares the ECB's monetary policy and the EU-wide permit markets of ETS 1 and ETS 2 with the rest of the Euro Area, whose emissions Z_t^{REU} co-determine the equilibrium carbon prices. Interactions with the rest of the world run through trade in goods and energy inputs, the CBAM levy on covered imports, and the accumulation of net foreign assets.

Keynesian Phillips curve, and a monetary policy rule. The EA shares its monetary authority with the domestic economy. Both regions generate greenhouse gas emissions linked to their level of activity.

2.2 Supply Side: Intermediate-Good Producers

Intermediate-good producers are monopolistically competitive firms that combine value added, non-electric energy (oil, gas, and coal burned directly in production), and electricity to produce differentiated goods. They face quadratic adjustment costs when resetting prices and when changing labor and electricity inputs, frictions that slow the economy's response to shocks.[8]

The typical firm faces a constant elasticity of substitution (CES) technology:

$$Y_t = A_t \left[\rho_{VA}^{\frac{1}{\theta_Y}} VA_t^{\frac{\theta_Y - 1}{\theta_Y}} + \rho_{NEL}^{\frac{1}{\theta_Y}} NEL_t^{\frac{\theta_Y - 1}{\theta_Y}} + (1 - \rho_{VA} - \rho_{NEL})^{\frac{1}{\theta_Y}} EL_{P,t}^{\frac{\theta_Y - 1}{\theta_Y}} \right]^{\frac{\theta_Y}{\theta_Y - 1}}, \quad (1)$$

where Y_t is output, A_t is total factor productivity (TFP), VA_t is value added (a com-

[8]Market power derives from the standard assumption of the existence of differentiated intermediate goods used in the production of the final good via a CES technology whose elasticity of substitution is subject to shocks giving rise to shocks on markups as specified in Appendix C.

posite of capital and labor), NEL_t is non-electric energy, and $EL_{P,t}$ is electricity used in production. The parameter θ_Y is the elasticity of substitution among the three inputs, while ρ_{VA} and ρ_{NEL} are the value-added and non-electric energy shares. TFP A_t is stochastic and its law of motion is specified in Appendix C.

Value added combines capital and labor through a CES function:

$$VA_t = \left[\rho_K^{\frac{1}{\theta_{VA}}} (u_t^K K_t)^{\frac{\theta_{VA}-1}{\theta_{VA}}} + (1-\rho_K)^{\frac{1}{\theta_{VA}}} \left(L_t \, e^{\epsilon_{L,Covid,t}}\right)^{\frac{\theta_{VA}-1}{\theta_{VA}}}\right]^{\frac{\theta_{VA}}{\theta_{VA}-1}}, \tag{2}$$

where K_t is the capital stock, L_t denotes labor inputs, u_t^K is the capital-utilization rate, θ_{VA} is the elasticity of substitution between capital and labor, and ρ_K is the capital share. The term $\epsilon_{L,Covid,t}$ is the transitory labor-hoarding shock that is zero outside the pandemic phase. For details, see Appendix A.

Emissions and Abatement Production generates emissions as a by-product arising directly from the production process itself and from the use of oil, gas, and coal burned directly in production. Emissions, in turn, can be partially abated by incurring extra costs. For simplicity, pollutant emissions in this (intermediate) sector, $Z_{Y,t}$, are directly anchored to production as follows

$$Z_{Y,t} = (1 - u_{Y,t}) \, \phi_Y \, Y_t^{\mu_Y} \, e^{\epsilon_{sz,t}}, \tag{3}$$

where $u_{Y,t} \in [0,1]$ is abatement effort, μ_Y is the elasticity of emissions with respect to output, ϕ_Y is a technology parameter, and $\epsilon_{sz,t}$ is a stochastic emissions shock common to the emitting sources (defined in Appendix C). Being subject to environmental regulation, firms must buy permits for their residual emissions at the carbon price $P_{Z,t}$, or else reduce emissions by incurring abatement costs

$$AC_t = \phi_1^Y \, u_{Y,t}^{\phi_2^Y} \, Y_t, \tag{4}$$

where ϕ_1^Y is the share of output needed to abate emissions entirely and $\phi_2^Y > 1$ governs the curvature of the abatement-cost schedule. We treat ϕ_1^Y as constant over the horizon considered: since our focus is the short to medium run, we abstract from the gradual decline in abatement costs (the backstop technology) that the DICE model embeds over much longer horizons.[9] Optimal abatement equates, at the margin, the cost of reducing one more unit of emissions to the carbon price: a higher $P_{Z,t}$ thus raises

[9] In the DICE model, ϕ_1^Y trends downward over time as mitigation technologies mature. See Nordhaus (2018) and Barrage and Nordhaus (2024). Over the business-cycle and transition horizons studied here, however, such long-run technological drift is of second-order importance, and holding the coefficient fixed isolates the macroeconomic effects of carbon pricing from those of exogenous abatement-cost improvements.

abatement effort, lowers residual emissions, and increases marginal production costs. This is the central producer-side transmission channel of ETS 1.

Abatement Adjustment Costs Unlike standard E-DSGE models, we do not let firms costlessly choose the environmental efficiency of their technology. Granting frictionless control over abatement would let firms minimize mitigation costs over the cycle and would understate the constraints that climate policy imposes on production and investment.[10] This is implausible at business-cycle frequencies, since changes in abatement effort reflect medium-term investment and technology adoption, and a large share of such investment is irreversible. Following Annicchiarico and Diluiso (2019), we therefore assume that adjusting abatement effort is costly and partially irreversible. The cost is given by a LINEX function, which penalizes the magnitude and, asymmetrically, the sign of the adjustment:

$$\mathcal{L}_t^{u_Y} = \frac{\vartheta^{u_Y}}{(\eta^{u_Y})^2}\left[\exp(-\eta^{u_Y}\,\Delta u_{Y,t}) + \eta^{u_Y}\,\Delta u_{Y,t} - 1\right], \qquad \Delta u_{Y,t} \equiv \frac{u_{Y,t}}{u_{Y,t-1}} - 1, \tag{5}$$

where $\vartheta^{u_Y} > 0$ scales the cost and $\eta^{u_Y} > 0$ governs its curvature and asymmetry. The function is differentiable and strictly convex: increases in effort raise costs roughly linearly, whereas reductions raise them exponentially, so that lowering abatement is disproportionately costly. This asymmetry captures the partial irreversibility of abatement investment.[11]

2.3 Supply Side: The Energy Sector

The energy sector consists of monopolistically competitive producers that supply the energy bundle demanded by intermediate-good firms and households. The bundle splits into electricity and non-electric energy, each, in turn, represented by a nested CES structure that allows the model to track the substitution among fossil fuels, renewables, and imported energy.

The electricity available in the economy, say EL_t, is used for production, as already described, and for consumption, as will be explained below. Total electricity is the result of a bundle of domestically produced electricity, $EL_{D,t}$, and imported electricity,

[10] Another alternative way of modelling this point could be the introduction of a trade-off between borrowing costs and abatement efforts that would limit the ability of firms to relax these constraints. This implies that firms use loans to finance all or at least a fraction of their input costs, which also include abatement spending.

[11] In DICE-based models, firms adjust abatement effort each quarter at no cost; see, e.g., Heutel (2012); Annicchiarico and Di Dio (2015). The flexibility of the control rate is among the most debated features of DICE, and stochastic variants such as Traeger (2014) and Cai and Lontzek (2019) likewise leave it unconstrained for tractability. In a DSGE setting, where the focus is the short run, such flexibility can be problematic.

$EL_{F,t}$:

$$EL_t = \left[\rho_{EL}^{\frac{1}{\theta_{EL}}} \, EL_{D,t}^{\frac{\theta_{EL}-1}{\theta_{EL}}} + (1-\rho_{EL})^{\frac{1}{\theta_{EL}}} \, EL_{F,t}^{\frac{\theta_{EL}-1}{\theta_{EL}}} \right]^{\frac{\theta_{EL}}{\theta_{EL}-1}}, \tag{6}$$

where $\theta_{EL} > 0$ is the elasticity of substitution between domestic and foreign electricity and $\rho_{EL} \in (0,1)$ is the domestic share.

Domestic electricity, in turn, is a CES composite of fossil-based generation $EL_{FOS,t}$ and renewable electricity $EL_{RES,t}$:

$$EL_{D,t} = \left[\rho_{EL_{CON}}^{\frac{1}{\theta_D}} \, EL_{FOS,t}^{\frac{\theta_D-1}{\theta_D}} + (1-\rho_{EL_{CON}})^{\frac{1}{\theta_D}} \, EL_{RES,t}^{\frac{\theta_D-1}{\theta_D}} \right]^{\frac{\theta_D}{\theta_D-1}}, \tag{7}$$

where $\theta_D > 0$ is the elasticity of substitution and $\rho_{EL_{CON}} \in (0,1)$ is the share of the fossil component which, in turn, combines a coal-oil composite $EL_{COAOIL,t}$ with natural gas $GAS_{EL,t}$:

$$EL_{FOS,t} = \left[\rho_{COAOIL}^{\frac{1}{\theta_{FOS}}} \, EL_{COAOIL,t}^{\frac{\theta_{FOS}-1}{\theta_{FOS}}} + (1-\rho_{COAOIL})^{\frac{1}{\theta_{FOS}}} \, GAS_{EL,t}^{\frac{\theta_{FOS}-1}{\theta_{FOS}}} \right]^{\frac{\theta_{FOS}}{\theta_{FOS}-1}}, \tag{8}$$

with $\theta_{FOS} > 0$ the coal-oil/gas elasticity and $\rho_{COAOIL} \in (0,1)$ the coal-oil share. The coal-oil composite aggregates coal $COA_{EL,t}$ and oil $OIL_{EL,t}$:

$$EL_{COAOIL,t} = \left[\rho_{COA}^{\frac{1}{\theta_{COAOIL}}} \, COA_{EL,t}^{\frac{\theta_{COAOIL}-1}{\theta_{COAOIL}}} + (1-\rho_{COA})^{\frac{1}{\theta_{COAOIL}}} \, OIL_{EL,t}^{\frac{\theta_{COAOIL}-1}{\theta_{COAOIL}}} \right]^{\frac{\theta_{COAOIL}}{\theta_{COAOIL}-1}}, \tag{9}$$

where $\theta_{COAOIL} > 0$ is the coal-oil elasticity and $\rho_{COA} \in (0,1)$ the coal share.

The progressively nested fossil structure (gas against a coal-oil composite, and coal against oil within it) reflects the limited and uneven substitutability across fuels in electricity generation.

Renewable electricity combines solar ($EL_{SOL,t}$), wind ($EL_{WIN,t}$), biomass ($EL_{BIO,t}$), and hydro ($EL_{HYD,t}$):

$$EL_{RES,t} = \left[\begin{array}{c} \rho_{EL_{SOL}}^{\frac{1}{\theta_{RES}}} EL_{SOL,t}^{\frac{\theta_{RES}-1}{\theta_{RES}}} + \rho_{EL_{WIN}}^{\frac{1}{\theta_{RES}}} EL_{WIN,t}^{\frac{\theta_{RES}-1}{\theta_{RES}}} + \rho_{EL_{BIO}}^{\frac{1}{\theta_{RES}}} EL_{BIO,t}^{\frac{\theta_{RES}-1}{\theta_{RES}}} \\ + (1-\rho_{EL_{SOL}} - \rho_{EL_{WIN}} - \rho_{EL_{BIO}})^{\frac{1}{\theta_{RES}}} EL_{HYD,t}^{\frac{\theta_{RES}-1}{\theta_{RES}}} \end{array} \right]^{\frac{\theta_{RES}}{\theta_{RES}-1}}, \tag{10}$$

where $\theta_{RES} > 0$ is the elasticity of substitution among renewable technologies and the ρ-parameters are shares in $(0,1)$. The high value of θ_{RES} embeds the strong substitutability across renewable sources, in contrast to the rigid fossil nests.

Each renewable technology is produced with a Cobb-Douglas technology that combines a technology-specific capital input with a fixed natural-resource endowment. For $i \in \{\text{SOL}, \text{WIN}, \text{BIO}, \text{HYD}\}$:

$$EL_{i,t} \;=\; A_{i,t}\, K_{i,t}^{\alpha_i}\, F_i^{1-\alpha_i}, \tag{11}$$

where $A_{i,t}$ is productivity in technology i, $K_{i,t}$ the capital input, F_i the natural-resource endowment, and $\alpha_i \in (0,1)$. This specification links installed capacity to renewable production, enabling clean-capital accumulation to drive renewable energy expansion.

Finally, non-electric energy is generated from oil, gas and coal:

$$NEL_t = \left[\begin{array}{c} \rho_{NEL,OIL}^{\frac{1}{\theta_{NEL}}}\, OIL_{NEL,t}^{\frac{\theta_{NEL}-1}{\theta_{NEL}}} + \rho_{NEL,GAS}^{\frac{1}{\theta_{NEL}}}\, GAS_{NEL,t}^{\frac{\theta_{NEL}-1}{\theta_{NEL}}} \\ +(1-\rho_{NEL,OIL}-\rho_{NEL,GAS})^{\frac{1}{\theta_{NEL}}}\, COA_{NEL,t}^{\frac{\theta_{NEL}-1}{\theta_{NEL}}} \end{array} \right]^{\frac{\theta_{NEL}}{\theta_{NEL}-1}}, \tag{12}$$

where $\theta_{NEL} > 0$ is the elasticity of substitution across the three inputs and $\rho_{NEL,OIL}, \rho_{NEL,GAS} \in (0,1)$ are share parameters, with the residual share assigned to coal. The production side of the economy is represented in Figure 2.

Emissions Fossil-based electricity generation and the non-electric energy aggregate both emit carbon. Emissions in the two nests are

$$Z_{EL,t} = \phi_{EL}\,(1-u_{EL,t})\, EL_{FOS,t}^{\mu_{EL}}\, e^{\epsilon_{sz,t}}, \tag{13}$$

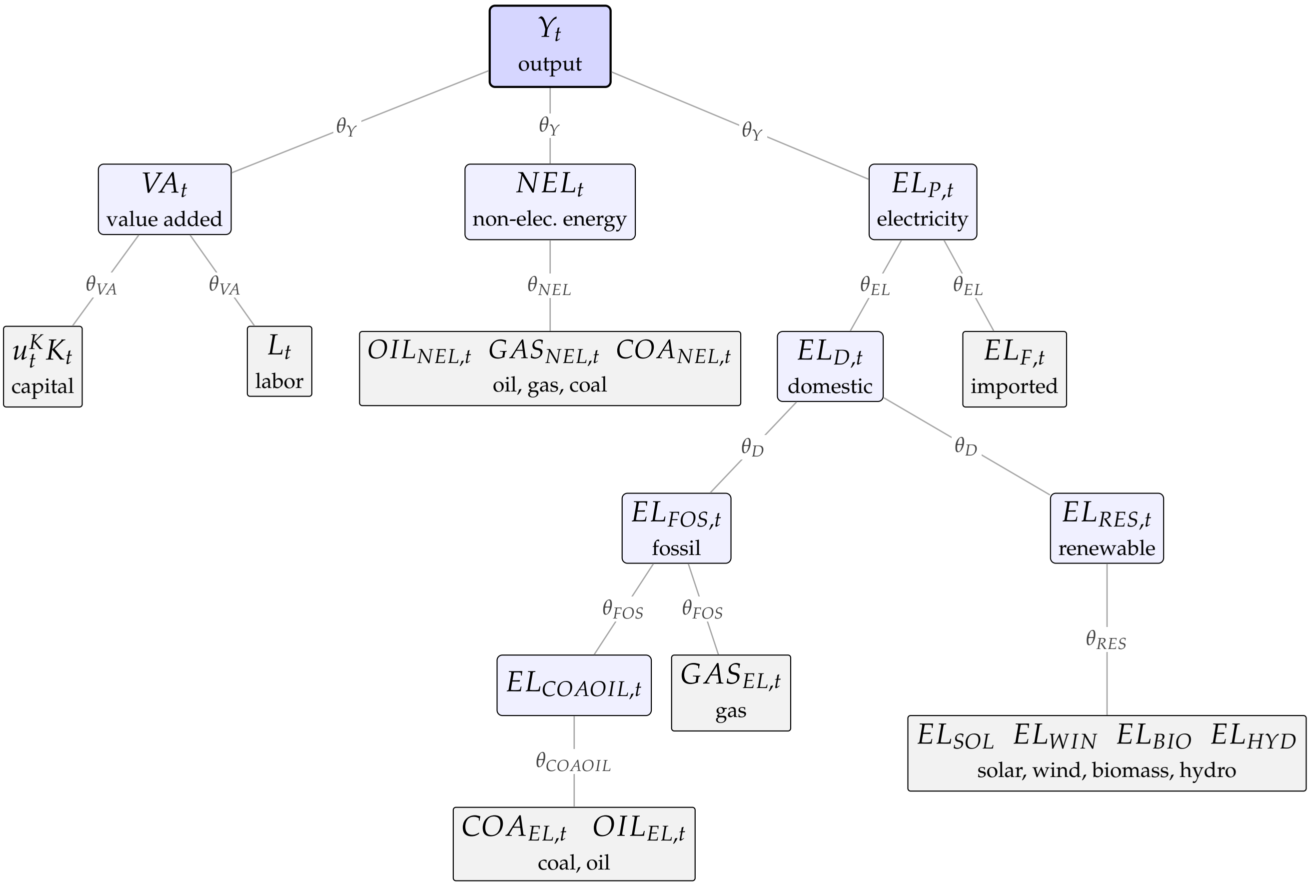
$$Z_{NEL,t} = \phi_{NEL}\, NEL_t^{\mu_{NEL}}\, e^{\epsilon_{sz,t}}, \tag{14}$$

where $\phi_{EL}, \phi_{NEL} > 0$ are technology parameters, $\mu_{EL}, \mu_{NEL} > 0$ the emissions elasticities in the respective nests, $u_{EL,t} \in [0,1]$ is abatement effort in electricity generation, and $\epsilon_{sz,t}$ is the common emissions shock. Unlike electricity generation, the non-electric energy aggregate is not endowed with an abatement margin: since $Z_{NEL,t}$ accounts for only a small share of total covered emissions, modeling endogenous abatement in this nest would add little to the analysis, and we omit it for parsimony.

2.4 Demand Side: Households

The domestic economy is populated by a continuum of households of mass one, split into two types: Ricardian (R) and non-Ricardian (NR). A share s_R is Ricardian and the remaining $1 - s_R$ is non-Ricardian. Ricardian households have access to financial markets and smooth consumption intertemporally; non-Ricardian households are hand-to-mouth consumers who spend their entire current income each period. The presence of liquidity-constrained households is central to the distributional analysis,

Figure 2: Nested Production Structure of GEEM



Notes: Shaded boxes are CES aggregators; light boxes are primary inputs or imported fuels. Italic labels on each branch denote the elasticity of substitution governing that nest. Output Y_t combines value added, non-electric energy, and electricity (θ_Y); value added combines capital and labor (θ_{VA}); non-electric energy nests oil, gas and coal inputs in a CES aggregate (θ_{NEL}); electricity nests domestic against imported supply (θ_{EL}), then fossil against renewable generation (θ_D), with the fossil branch further splitting gas from a coal–oil composite (θ_{FOS}, θ_{COAOIL}) and the renewable branch aggregating solar, wind, biomass, and hydro (θ_{RES}).

since it makes a fraction of the economy respond one-for-one to changes in current disposable income and, hence, to energy and carbon prices.

Both types of households derive utility from a consumption bundle of final goods and energy and from leisure. The lifetime utility of household $i \in \{R, NR\}$ is

$$E_0 \sum_{t=0}^{\infty} \beta^t e^{\epsilon_{c,t}} \left[\log\left(C_t^i e^{\epsilon_{C,Covid,t}} - h_C^i \bar{C}_{t-1}^i \right) - \frac{\omega_L}{1+\nu_L} (L_t^i)^{1+\nu_L} \right], \tag{15}$$

where $\beta \in (0, 1)$ is the steady-state discount factor and $\epsilon_{c,t}$ is a stochastic disturbance that shifts the intertemporal allocation of consumption, defined in Appendix C, C_t^i is total consumption of household i, $h_C^i \in [0, 1)$ is the habit-persistence parameter, $\bar{C}_{t-1}^i$ is (external) lagged consumption, L_t^i is labor supply, ν_L is the inverse of the Frisch elasticity of labor supply, and $\omega_L > 0$ scales the disutility of labor. The term $\epsilon_{C,Covid,t}$ is the Covid shock to consumption, which temporarily constrains private spending during the pandemic period (see Appendix A). Habit formation introduces inertia in consumption, which is particularly strong for unconstrained households.

Ricardian households maximize their lifetime utility, subject to the flow budget constraint:

$$
\begin{aligned}
P_{C,t}C_t^R(1+\tau_t^C) + B_t^R + S_t B_t^{F,R} + P_{I,t}I_t^R + P_{I_{RES},t}I_{RES,t}^R = & \left(1-\tau_t^L-\tau_{h,t}^{W_L}\right) W_t L_t^R + \\
& + R_{t-1}B_{t-1}^R + R_{t-1}^* S_t B_{t-1}^{F,R} + \\
& + \tau_t^K \delta_K P_{I,t} u_t^K K_t^R + \\
& + (1-\tau_t^K) r_t^K P_{I,t} u_t^K K_t^R + \\
& + \tau_t^{K_{RES}} \delta_{K_{RES}} P_{I_{RES},t} K_{RES,t}^R + \\
& + (1-\tau_t^{K_{RES}}) r_t^{K_{RES}} P_{I_{RES},t} K_{RES,t}^R + \\
& + tcrk_t P_{I,t} I_t^R + tcrk_{RES,t} P_{I_{RES},t} I_{RES,t}^R + \\
& - TAX_t^R + Tr_t^R + V_t^R - ADJ_t^R,
\end{aligned} \tag{16}
$$

where $P_{C,t}$ is the consumption price index and τ_t^C is the tax rate on consumption; I_t^R and $I_{RES,t}^R$ denote investment in intermediate goods and in the RES sector respectively; $P_{I,t}$ and $P_{I_{RES},t}$ are the prices of the two types of investment goods; $tcrk$, $tcrk_{RES}$, τ_t^K and $\tau_t^{K_{RES}}$ denote the subsidies and tax rates on investment and capital in both intermediate goods and the RES sector; δ_K and $\delta_{K_{RES}}$ are the depreciation rates of capital; B_t^R and $B_t^{F,R}$ are the amount of domestic (government) and foreign bonds (denominated in foreign currency) purchased by the Ricardian households; R_t is the nominal risk free interest rate; R_t^* is the risk adjusted interest rate on foreign assets; S_t denotes the nominal exchange rate defined as the home currency per unit of foreign currency; W_t is the wage; τ_t^L and $\tau_{h,t}^{W_L}$ are the labor-income tax rate and the social-security contribution rate levied on households; TAX_t^R and Tr_t^R are lump-sum taxes and transfers; V_t^R denotes profits earned from the ownership of intermediate good producing firms, electricity producing firms, importing and exporting firms. Finally, the term ADJ_t^R represents a catchall variable capturing the overall adjustment costs sustained by households when re-setting wages, changing investments in RES and physical capital and adjusting the level of capital utilization.

Capital accumulation is subject to a capital-quality shock $\Psi_{0,t}$, which scales the effective value of installed capital in the intermediate-goods sector, so that effective capital is $\Psi_{0,t}K_t$. This is a way to capture unexpected obsolescence or shifts in economic depreciation, in line with DSGE models with financial frictions (Gertler and Karadi, 2011). The capital laws of motion are

$$
K_{t+1}^R = (1-\delta_K)\,\Psi_{0,t}K_t^R + I_t^R, \tag{17}
$$

$$K^R_{RES,t+1} = (1 - \delta_{K_{RES}}) K^R_{RES,t} + I^R_{RES,t}. \tag{18}$$

Non-Ricardian households, by contrast, face a period-by-period budget constraint that equates consumption to current labor income net of taxes plus transfers:

$$P_{C,t} C^{NR}_t = \left(1 - \tau^{L_{NR}}_t - \tau^{W_{L_{NR}}}_{h,t}\right) W_t L^{NR}_t - TAX^{NR}_t + Tr^{NR}_t. \tag{19}$$

where all variables are as in (16) and the superscript NR stands for "non-Ricardian".

Consumption Bundles Both household types consume a composite of final goods and energy:

$$C^i_t = \left[\alpha^{\frac{1}{\theta_C}}_{i,C_Y} \left(C^i_{Y,t}\right)^{\frac{\theta_C - 1}{\theta_C}} + (1 - \alpha_{i,C_Y})^{\frac{1}{\theta_C}} \left(C^i_{F,t}\right)^{\frac{\theta_C - 1}{\theta_C}}\right]^{\frac{\theta_C}{\theta_C - 1}}, \tag{20}$$

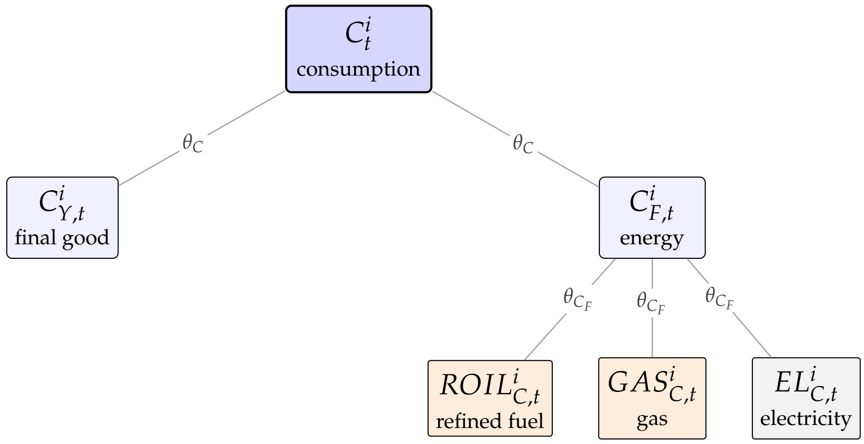
where $C^i_{Y,t}$ is consumption of the final good (non-tradable), $C^i_{F,t}$ is energy consumption, $\theta_C > 0$ is the elasticity of substitution between goods and energy, and $\alpha_{i,C_Y} \in (0,1)$ is the goods share that is specific to each type of consumer. Energy consumption is itself a bundle of refined fuel, gas, and electricity:

$$C^i_{F,t} = \left[\begin{array}{c} \alpha^{\frac{1}{\theta_{C_F}}}_{i,ROIL} \left(ROIL^i_{C,t}\right)^{\frac{\theta_{C_F} - 1}{\theta_{C_F}}} + \alpha^{\frac{1}{\theta_{C_F}}}_{i,GAS} \left(GAS^i_{C,t}\right)^{\frac{\theta_{C_F} - 1}{\theta_{C_F}}} \\ + (1 - \alpha_{i,ROIL} - \alpha_{i,GAS})^{\frac{1}{\theta_{C_F}}} \left(EL^i_{C,t}\right)^{\frac{\theta_{C_F} - 1}{\theta_{C_F}}} \end{array}\right]^{\frac{\theta_{C_F}}{\theta_{C_F} - 1}}, \tag{21}$$

where $ROIL^i_{C,t}$ is refined-fuel consumption, $GAS^i_{C,t}$ is gas consumption, $EL^i_{C,t}$ is electricity consumption, $\theta_{C_F} > 0$ is the elasticity of substitution among the three energy goods, and $\alpha_{i,ROIL}, \alpha_{i,GAS} \in (0,1)$ are the fuel and gas shares (with the residual share assigned to electricity). The low estimated value of θ_{C_F} implies that households substitute away from carbon-intensive energy only sluggishly, which shapes the consumption response to ETS 2. The carbon price on refined oil and gas, $p_{z_F,t}$, still expressed as a relative price, enters the corresponding consumer prices and is the direct channel through which ETS 2 reaches households.

Cost minimization over these bundles yields the standard CES demand functions, in which each component depends on its relative price and on the relevant bundle. The demands for refined fuel, gas, and electricity depend on their prices inclusive of the ETS 2 carbon price $p_{z_F,t}$. The associated consumer-price indices (for the goods bundle, the energy bundle, and overall consumption) follow from the same aggregators and embed the consumption tax rate τ^C_t. Two stochastic disturbances, $\epsilon_{spc,t}$ and $\epsilon_{spe,t}$, shift the overall consumer-price and energy-price indices respectively and are defined in Appendix C. Figure 3 summarizes the nested structure of consumption.

Figure 3: Nested Consumption Structure of GEEM



Notes: Nested CES structure of household consumption in GEEM, common to both household types $i \in \{R, NR\}$. Shaded boxes are CES aggregators; light boxes are consumption goods. Total consumption C_t^i combines the final good and an energy bundle (θ_C); the energy bundle in turn combines refined fuel, gas, and electricity (θ_{C_F}).

Labor Supply and Wage Setting Each household provides a differentiated labor service in a monopolistically competitive market and therefore holds a degree of market power over its own wage. A competitive labor union (equivalently, a labor packer) bundles these differentiated services into the homogeneous labor input L_t hired by intermediate-good firms, using a CES aggregator with elasticity of substitution $\sigma_L > 1$. The variable L_t^i in the utility function (15) should thus be read as each household's contribution to this bundle, and W_t denotes the common nominal wage.

Because labor services are imperfect substitutes, wage setters face a downward-sloping demand for their own labor and set the nominal wage as a markup over the marginal rate of substitution between consumption and leisure. The desired markup is $\mu_t^W = \sigma_L/(\sigma_L - 1)$, up to a stochastic wage disturbance, so that σ_L governs the degree of competition in the labor market and hence the size of the markup over the steady-state level μ^W. Wages are subject to adjustment costs, which generate nominal wage rigidity and slow the pass-through of shocks to labor income. The labor-demand is also hit by the Covid labor-market shock $\epsilon_{L,Covid}$, which captures the wedge between hours worked and hours paid under the short-time-work schemes in place during the pandemic (see Appendix A). Since both household types face the same labor-demand schedule and the same wage, they supply identical hours; differences in their consumption responses therefore arise on the income side: Ricardians smooth through saving and asset holdings, non-Ricardians do not. The wage markup is subject to a stochastic disturbance defined in Appendix C.

2.5 Export and Import Sectors

A continuum of monopolistically competitive exporting firms transforms domestic intermediate goods into exportable goods using a linear technology. These firms buy intermediate goods from domestic producers and sell them abroad, charging a markup μ_{exp} over marginal cost, and face adjustment costs when resetting prices. Total export demand EXP_t depends on RoW demand and on the relative price of domestic goods, $S_t P^*_{X,t}/P_t$, where $P^*_{X,t}$ is the export price in foreign currency, S_t denotes the nominal exchange rate, defined as units of domestic currency per unit of RoW currency, and P_t is the domestic final-good price index. The export markup is subject to a stochastic disturbance, defined in Appendix C.

A continuum of monopolistically competitive importing firms operates across several segments. They import coal ($COA_t = COA_{EL,t} + COA_{NEL,t}$), natural gas ($GAS_t = GAS_{EL,t} + GAS_{NEL,t} + GAS_{C,t}$), crude oil ($OIL_t = OIL_{EL,t} + OIL_{NEL,t}$), refined oil ($ROIL_t$), and electricity $EL_{F,t}$. As described in the previous sections, these energy inputs are used for the electricity sector, production and consumption. Finally, importing firms purchase two types of foreign intermediate goods: ($IMPF_t$) not subject to the CBAM regulation and ($IMP_{CBAM,t}$) that is the imports under the CBAM regulation. Importers not subject to the CBAM regulation charge a markup μ_{imp} over the foreign-currency price of each imported good, so that the domestic price of a generic imported item is a constant proportion of its foreign price converted at the exchange rate S_t according to the following equation (under symmetry):

$$P_{\hat{N},t} = \mu_{imp} S_t P^*_{\hat{N},t} \tag{22}$$

where $P_{\hat{N},t}$ is the generic price for a vector including the variety of imported materials: $\hat{N}_t = \{COA_t, GAS_t, OIL_t, ROIL_t, EL_{F,t}, IMPF_t\}$, while μ_{imp} is the price markup of the importers. The import markup, in turn, is hit by a stochastic disturbance, and the import prices of oil and gas are subject to their own stochastic disturbances, all defined in Appendix C. The importers subject to the CBAM-type regulation face a similar equation including the CBAM-type border carbon tariff on their imports:

$$P_{N_{C\hat{B}AM},t} = \mu_{imp} S_t P^*_{\hat{N},t} + P^{CBAM}_{Z,t} \tag{23}$$

where $N_{C\hat{B}AMt} = \{IMP_{CBAM,t}\}$ and $P^{CBAM}_{Z,t}$ is the effective carbon tariff rate faced by imported products that is jointly determined by the bilateral (domestic and foreign) carbon-price differential and the net taxable carbon intensity of import. See Section 2.11 for more details.

2.6 Euro Area and Rest of the World

The Euro Area (EA) and rest-of-the-world (RoW) blocks are modeled in reduced form. Each consists of an IS, based on a Euler equation, a New Keynesian Phillips curve, and a Taylor rule, and both abstract from capital accumulation. The two blocks capture external demand for domestic exports and the transmission of common shocks and policies. The EA shares its monetary authority with the domestic economy. The RoW block is subject to a demand disturbance (ϵ_{RoW}), while the EA block is subject to a demand disturbance (ϵ_{YEA}) and an inflation disturbance (ϵ_{INFEA}); all are defined in Appendix C.

2.7 Final-Good Producers

Perfectly competitive, symmetric firms produce the final non-tradable good $Y_{NT,t}$ by combining a bundle of domestically produced intermediate goods $Y_{H,t}$ (that is the domestic absorption of domestic production) with a bundle of imported intermediate goods subject or not to the CBAM, $IMP_{CBAM,t}$ and $IMPF_t$. The technology is CES:

$$Y_{NT,t} = \begin{bmatrix} (1-\alpha_{IMPF}-\alpha_{IMP_{CBAM}})^{\frac{1}{\sigma_{IMP}}} Y_{H,t}^{\frac{\sigma_{IMP}-1}{\sigma_{IMP}}} \\ +\alpha_{IMPF}^{\frac{1}{\sigma_{IMP}}} IMPF_t^{\frac{\sigma_{IMP}-1}{\sigma_{IMP}}} + \alpha_{IMP_{CBAM}}^{\frac{1}{\sigma_{IMP}}} IMP_{CBAM,t}^{\frac{\sigma_{IMP}-1}{\sigma_{IMP}}} \end{bmatrix}^{\frac{\sigma_{IMP}}{\sigma_{IMP}-1}}, \tag{24}$$

where $\sigma_{IMP} > 0$ is the elasticity of substitution between domestic and imported intermediate goods; $\alpha_{IMPF} \in (0,1)$ is the import share of goods not subject to the CBAM regulation, while $\alpha_{IMP_{CBAM}}$ is the corresponding share in import under CBAM regulation. The sum of the two shares measures the degree of openness of the economy. Cost minimization delivers the usual CES demands for $Y_{H,t}$, $IMPF_t$ and $IMP_{CBAM,t}$ as functions of their relative prices, P_t^D/P_t, $P_{\hat{N},t}/P_t$ and $P_{N_{\hat{CBAM}},t}/P_t$, where P_t^D is the price index of domestic intermediate goods. Under perfect competition and zero profits, the final-good price index P_t is the CES aggregate of these three prices.

2.8 Public Sector

The public sector comprises a national fiscal authority and the common monetary authority. The fiscal authority manages government revenues, expenditures, and debt, while the central bank, in common with the rest of the EA, sets the policy rate according to a Taylor-type rule.[12]

Government Budget The flow budget constraint of the government evolves as

[12]Environmental policy belongs to the fiscal authority and is presented separately in Section 2.11.

$$B_t = R_{t-1}B_{t-1} + P_{E,t}G_t + Tr_t - TAX_t - LTAX_t - CTAX_t \\ - KTAX_t - EXCTOT_t - P_{Z,t}(Z_{Y,t} + Z_{EL,t}) - p_{z_F,t}Z^{ETS2} - P_{Z,t}^{CBAM} IMP_{CBAM,t} + \epsilon_{sdr,t}, \tag{25}$$

where B_t is end-of-period public debt, R_{t-1} is the gross interest rate on debt, $P_{E,t}$ is the price of the final good purchased by the government, G_t is real public consumption, and Tr_t are aggregate transfers to households. The terms TAX_t, $LTAX_t$, $CTAX_t$, $KTAX_t$, and $EXCTOT_t$ denote, respectively, lump-sum taxes, labor taxes, consumption taxes, capital income taxes net of subsidies, and excise taxes; $P_{Z,t}(Z_{Y,t} + Z_{EL,t})$ is the revenue from the sale of ETS 1 emission permits; $p_{z_F,t}Z^{ETS2}$ is the revenue from the sale of ETS 2 emission permits; $P_{Z,t}^{CBAM} IMP_{CBAM,t}$ is the revenues from the CBAM regulation; and $\epsilon_{sdr,t}$ is a stochastic disturbance to the public budget, defined in Appendix C.

Transfers and lump-sum taxes are population-weighted averages across the two household types,

$$Tr_t = s_R Tr_t^R + (1 - s_R)Tr_t^{NR}, \qquad TAX_t = s_R TAX_t^R + (1 - s_R)TAX_t^{NR}. \tag{26}$$

Labor-tax revenue aggregates, for each type, the personal labor-income tax and the social-security contributions levied on households and firms:

$$LTAX_t = \left[s_R L_t^R W_t + (1 - s_R)\, L_t^{NR} W_t\right] \left(\tau_t^L + \tau_{h,t}^{W_L} + \tau_{f,t}^{W_L}\right), \tag{27}$$

while consumption-tax revenues are

$$CTAX_t = \tau_t^C P_{C,t}[s_R C_t^R + (1 - s_R)C_t^{NR}]. \tag{28}$$

Capital-tax revenue net of investment subsidies is

$$KTAX_t = \tau_t^K (r_t^K - \delta_K) P_{I,t} u_t^K K_t - tcrk_t P_{I,t} I_t \\ + \tau_t^{K_{RES}} (r_t^{K_{RES}} - \delta_{K_{RES}}) P_{I_{RES},t} K_{RES,t} - tcrk_{RES,t} P_{I_{RES},t} I_{RES,t}, \tag{29}$$

where τ_t^K and $\tau_t^{K_{RES}}$ are the tax rates on standard and renewable-energy capital, r_t^K and $r_t^{K_{RES}}$ are the rental rates of physical and renewable capital, δ_K and $\delta_{K_{RES}}$ are the corresponding depreciation rates, $P_{I,t}$ and $P_{I_{RES},t}$ are the investment-goods prices, u_t^K is capital utilization, K_t and $K_{RES,t}$ are the capital stocks, I_t and $I_{RES,t}$ are investment flows, and $tcrk_t$, $tcrk_{RES,t}$ are investment-tax-credit rates. Excise revenue is

$$EXCTOT_t = \tau_t^{ROIL} ROIL_t + \tau_t^{GAS} GAS_t, \tag{30}$$

where τ_t^{ROIL} and τ_t^{GAS} are the excise rates on refined fuel and gas, and $P_{ROIL,t}$, $P_{GAS,t}$ the corresponding prices.

The lump-sum tax TAX_t is the residual fiscal instrument: it adjusts endogenously to public debt so as to keep the government budget on a stable path, however in the mitigation scenarios this adjustment channel will be switched off temporarily so to avoid automatic redistribution of carbon revenues. Public consumption G_t follows an exogenous autoregressive process around its deterministic steady-state level G, driven by a spending disturbance $\epsilon_{g,t}$ defined in Appendix C.

Monetary Policy The common central bank sets the short-term nominal rate $R_{EA,t}$ according to a Taylor-type rule with interest-rate smoothing, responding to EA inflation, EA output growth, and the exchange rate:

$$\frac{R_{EA,t}}{\overline{R_{EA}}} = \left(\frac{R_{EA,t-1}}{\overline{R_{EA}}}\right)^{\kappa_r} \left[\left(\frac{\Pi_{EA,t}}{\overline{\Pi}_{EA}}\right)^{\kappa_\pi} \left(\frac{Y_{EA,t}}{Y_{EA,t-1}}\right)^{\kappa_y} \left(\frac{S_t}{\overline{S}}\right)^{\kappa_S}\right]^{1-\kappa_r} e^{\epsilon_{R,t}}, \tag{31}$$

where $\Pi_{EA,t}$ and $Y_{EA,t}$ are EA inflation and output, S_t is the exchange rate, barred variables denote steady-state levels, and $\kappa_r, \kappa_\pi, \kappa_y, \kappa_S$ are the smoothing, inflation, output growth, and exchange-rate response coefficients. The term $\epsilon_{R,t}$ is a monetary-policy disturbance defined in Appendix C.

Domestic Rate and Sovereign Spread Domestic agents borrow and lend at a domestic rate R_t, which is the short-term rate plus a spread:

$$R_t = R_{EA,t} + spread_t, \tag{32}$$

where the spread $spread_t$ reflects term premia, sovereign risk, and financial frictions, and is modeled as increasing in the deviation of the domestic debt-to-output ratio from its EA counterpart:

$$spread_t = \rho_{spread}\, spread_{t-1} + \beta_{spread}\left(\frac{B_t}{P_t Y_t} - \frac{B_{EA,t}}{P_{EA,t} Y_{EA,t}}\right) + \nu_{spread,t}, \tag{33}$$

where $\rho_{spread} \in [0, 1)$ is the persistence of the spread, $\beta_{spread} > 0$ is its sensitivity to relative indebtedness, $B_t/(P_t Y_t)$ is the domestic debt-to-output ratio (with B_t public debt, P_t the final-good price index, and Y_t domestic output), $B_{EA,t}/(P_{EA,t} Y_{EA,t})$ is the corresponding EA ratio (with $B_{EA,t}$, $P_{EA,t}$, and $Y_{EA,t}$ the EA debt, price index, and output), and $\nu_{spread,t}$ is an i.i.d. shock. This channel links fiscal sustainability to domestic financing conditions: a deterioration of the domestic debt position relative to the EA raises the spread and hence the long-term rate, so that carbon-revenue leakage, by raising debt, feeds back into borrowing costs.

2.9 Aggregation and Market Clearing

Aggregate quantities follow from the household shares. Since only Ricardian households own capital and trade bonds, the economy-wide stocks of capital, renewable-energy capital, investment, and domestic and foreign bonds are the Ricardian holdings scaled by the Ricardian share s_R:

$$K_t = s_R K_t^R, \quad K_{RES,t} = s_R K_{RES,t}^R \tag{34}$$

$$I_t = s_R I_t^R, \quad I_{RES,t} = s_R I_{RES,t}^R, \tag{35}$$

$$B_t = s_R B_t^R, \quad B_t^F = s_R B_t^{F,R}, \tag{36}$$

where the superscript R denotes Ricardian holdings and the unsuperscripted variables are the corresponding aggregates. Total renewable-energy capital is the sum of the technology-specific stocks:

$$K_{RES,t} = K_{WIN,t}^{RES} + K_{HYD,t}^{RES} + K_{BIO,t}^{RES} + K_{SOL,t}^{RES}, \tag{37}$$

with $K_{i,t}^{RES}$ the capital installed in renewable technology $i \in \{\text{WIN}, \text{HYD}, \text{BIO}, \text{SOL}\}$.

Consumption aggregates, by contrast, are population-weighted averages across both household types, since both consume:

$$C_t = s_R C_t^R + (1 - s_R) C_t^{NR}, \tag{38}$$

$$C_{Y,t} = s_R C_{Y,t}^R + (1 - s_R) C_{Y,t}^{NR}, \tag{39}$$

$$C_{F,t} = s_R C_{F,t}^R + (1 - s_R) C_{F,t}^{NR}, \tag{40}$$

where C_t is total consumption, $C_{Y,t}$ final-good consumption, and $C_{F,t}$ energy consumption. The same weighting applies to the individual energy goods:

$$ROIL_t = s_R ROIL_t^R + (1 - s_R) ROIL_t^{NR}, \tag{41}$$

$$GAS_{C,t} = s_R GAS_{C,t}^R + (1 - s_R) GAS_{C,t}^{NR}, \tag{42}$$

$$EL_{C,t} = s_R EL_{C,t}^R + (1 - s_R) EL_{C,t}^{NR}, \tag{43}$$

with $ROIL_t$, GAS_t, and $EL_{C,t}$ aggregate household consumption of refined fuel, gas, and electricity.

$$EL_t = EL_{P,t} + EL_{C,t}. \tag{44}$$

All investment goods used to build renewable-energy capital are imported, so total imports comprise coal (COA_t), crude oil (OIL_t), gas (GAS_t), refined oil ($ROIL_t$), and electricity $EL_{F,t}$, foreign intermediate goods ($IMPF_t$) and ($IMP_{CBAM,t}$) imports under the CBAM regulation.

2.10 External Balance and Resource Constraint

The economy interacts with the rest of the world through its net foreign asset position, denominated in domestic currency, which evolves as

$$S_t B_t^F = R_{t-1}^* \, S_t B_{t-1}^F + S_t P_{X,t}^* EXP_t - P_t IMPT_t, \tag{45}$$

where B_t^F is the net stock of foreign assets, S_t is the nominal exchange rate, R_{t-1}^* is the gross foreign interest rate, $P_{X,t}^*$ is the export price in foreign currency, EXP_t are exports, P_t is the domestic final-good price index, and $IMPT_t$ denotes total imports, including imported goods and services (those under CBAM regulation and those not subject to it); coal, oil, gas and imported electricity to firms; the imported fuel, gas, and electricity sold to households. The accumulation of foreign assets thus equals the trade surplus plus the return on the existing foreign position.

The aggregate resource constraint requires that domestic output be absorbed by private and public demand, net exports, and the real costs incurred in adjustment and abatement:

$$Y_t = \frac{P_{C_Y,t}}{P_t}\big(C_{Y,t} + I_t + G_t\big) + \frac{S_t P_{X,t}^*}{P_t} EXP_t - IMPT_t + ADJ_t + AC_t + \epsilon_{sy,t}, \tag{46}$$

where Y_t is domestic output, $C_{Y,t}$ is final-good consumption, I_t is total investment, G_t is public consumption, EXP_t and $IMPT_t$ are exports and total imports, and the relative prices $P_{C_Y,t}/P_t$ and $S_t P_{X,t}^*/P_t$ convert each demand component into units of domestic output. The term ADJ_t collects the economy-wide adjustment costs (on prices, wages, labor, investment, and energy use), while AC_t is the total abatement cost borne by intermediate-good and electricity producers. The presence of AC_t in the resource constraint makes explicit that abatement is a genuine resource cost: mitigation diverts output away from consumption and investment, which is one of the channels through which carbon pricing weighs on aggregate activity. Finally, $\epsilon_{sy,t}$ is an aggregate demand disturbance, defined in Appendix C.

2.11 Environmental Policy

The domestic economy operates under the European Emissions Trading System (EU ETS), a cap-and-trade regime, complemented by a border mechanism on imports. Under the ETS, a European authority issues emission permits to producers at the price consistent with an overall emissions cap. The permit supply is fixed by the cap, so that the carbon price is determined endogenously by permit demand in the EU-wide market.[13]

The environmental block comprises three instruments. The first is EU ETS 1, which prices emissions from energy-intensive producers and power generation. The second is EU ETS 2, a separate trading system that extends carbon pricing to refined oil and gas used by households and small final users for heating and transport. The third is the Carbon Border Adjustment Mechanism (CBAM), which applies the domestic carbon price to the carbon embodied in imports, so that foreign producers face the same carbon cost as domestic ones. The remainder of this subsection describes each instrument in turn.

EU ETS 1 The first system applies to the emission-intensive producing sectors: fossil-based electricity generation and the intermediate-good production. Each sector chooses abatement optimally in response to the prevailing carbon price. Grandfathering is ruled out, so that all permits are priced and revenue flows are fully market-based and comparable across agents. The aggregate ETS 1 cap, set by policy at the EU level, is denoted $\overline{Z}^{ETS1}$. Market clearing requires that total covered emissions equal the cap:

$$\overline{Z}^{ETS1} = Z_{Y,t} + Z_{EL,t} + Z_t^{REU}, \tag{47}$$

where Z_t^{REU} denotes emissions from the rest of the European Union. The latter respond to the carbon price according to

$$Z_t^{REU} = \phi_1^{REU} \, Y_t^{REU} - \epsilon^{ETS1} \, P_{Z,t}, \tag{48}$$

where Y_t^{REU} is EU27 output, $\phi_1^{REU} > 0$ links output to baseline emissions, and $\epsilon^{ETS1} > 0$ is the elasticity of EU emissions with respect to the carbon price. The domestic caps on $Z_{Y,t}$ and $Z_{EL,t}$ are set exogenously by policy. Substituting (48) into (47) then pins down $P_{Z,t}$: a tighter domestic cap requires a higher carbon price to clear the EU-wide permit market. The resulting permit revenue, $P_{Z,t}(Z_{Y,t} + Z_{EL,t})$, accrues to the domestic government.

EU ETS 2 A second, separate trading system covers emissions from refined oil and gas used by households and small final users for heating and transport, in line with recent EU legislation. A distinct EU-level cap applies to these sectors, and the corres-

[13] Public intervention is justified by the pollution damages associated with global warming and climate change. These damages are commonly modeled either as negative externalities in the utility of individuals or as factors depressing technological efficiency; see Hassler et al. (2016). We do not model such climate-related damages explicitly. Over the horizon considered here their quantitative impact is negligible, and physical climate risks lie outside the scope of the paper. The focus is therefore on the economic implications of climate policy rather than on the environmental consequences of emission reductions.

ponding carbon price $p_{z_F,t}$ clears the EU-wide ETS 2 market. Market clearing requires that total covered emissions equal the cap:

$$\overline{Z}^{ETS2} = Z_{HH,t} + Z_t^{REU,ETS2}, \tag{49}$$

where $Z_{HH,t}$ are domestic emissions from the household sector, while the term $Z_t^{REU,ETS2}$ denotes emissions covered under ETS 2 in the rest of the EU, and is assumed to follow the reduced-form relationship

$$Z_t^{REU,ETS2} = \phi_2^{REU}\, Y_t^{REU} - \epsilon^{ETS2}\, p_{z_F,t}, \tag{50}$$

where $\phi_2^{REU} > 0$ links output, Y_t^{REU}, to baseline ETS 2 emissions and $\epsilon^{ETS2} > 0$ is the price elasticity of ETS 2 emissions. As in ETS 1, a tighter cap raises the carbon price, while a higher $p_{z_F,t}$ lowers emissions through greater abatement and reduced fuel consumption. Unlike ETS 1, however, $p_{z_F,t}$, still expressed as a relative price, enters household energy prices directly, so that ETS 2 transmits to the economy through consumers' real income and consumption bundle. This is the channel that makes the distributional effects of ETS 2 salient, and it lets the model trace the equity consequences of extending carbon pricing beyond industry and power generation.

Carbon Border Adjustment Mechanism - CBAM The CBAM extends the domestic carbon price to the carbon embodied in imports, so that foreign producers face the same carbon cost as domestic ones when selling into the domestic market. We model CBAM as a levy on imported carbon-intensive intermediate goods $IMP_{CBAM,t}$, proportional to their embodied carbon content and to the ETS 1 permit price. The endogenous CBAM charge is then given by

$$P_{Z,t}^{CBAM} = \phi_e \cdot \max\left(0,\, P_{Z,t} - P_e^f\right), \tag{51}$$

where ϕ_e converts the bilateral carbon-price differential into an effective unit charge, and P_e^f is the carbon price faced by the foreign import sector.

Equation (51) is a reduced-form representation of the price-equalization principle behind CBAM. The border charge is activated only when the domestic carbon price exceeds the foreign one, which avoids a negative adjustment that would amount to a border subsidy. The parameter ϕ_e can be read as the average embodied carbon content of CBAM-covered imports scaled by the effective regulatory coverage of the mechanism. Hence the charge rises with the EU permit price and falls as carbon pricing in the exporting country becomes more stringent.[14] The CBAM charge enters directly

[14]The specification abstracts from product-specific emissions reporting, verification procedures, and transitional free allowances, which would require a more detailed representation of foreign production

the import-price equation as an additional cost wedge (see equation (23)), raising the relative price of covered imports.

3 Taking the Model to the Data

This section describes how the model is taken to the data and the calibration strategy. A subset of parameters is calibrated on steady-state ratios and on microeconomic data on Italian household expenditure. The remaining parameters are estimated with Bayesian methods on quarterly Italian data over 1999Q1–2024Q4, allowing for time-varying volatility to accommodate the pandemic period. We then check the model against the unconditional moments of the data.

3.1 Data, Shocks, and Estimation Strategy

The estimation relies on quarterly time series for 21 macroeconomic and environmental variables, covering real activity and its components, labor market variables, prices and interest rates, fiscal aggregates, energy prices, external variables, and greenhouse gas emissions for Italy and the EU27. The sample is 1999Q1–2024Q4, with data drawn mainly from Eurostat quarterly national accounts compiled according to ESA 2010 (Eurostat, 2026b, 2013). All series are seasonally adjusted, and a set of transformations ensures consistency with the model's balanced-growth path and stationarity of relative prices. The complete list of observables and transformations is reported in Appendix C.

The model includes one shock for each observed series plus two transitory COVID-19 disturbances. Each shock follows a first-order autoregressive process with Gaussian innovations; measurement errors are allowed for a subset of the observables. The full specification of the shock processes is given in Table C.1 in Appendix C. Parameters and shocks are estimated by Bayesian inference, which combines priors with the likelihood of the observed data and delivers a coherent quantification of uncertainty (see, e.g., An and Schorfheide, 2007). Priors reflect values commonly employed in the DSGE literature while remaining loose enough to let the data speak; the subset of parameters to be estimated is selected with the identification test of Iskrev (2010).[15]

The short-lived but unprecedented volatility of 2020–21 poses a challenge for estimation: quarterly output fluctuations during 2020 are extraordinary relative to the rest of the sample, and a homoskedastic Kalman filter cannot absorb them without contaminating the inference on the structural parameters. We deal with this in two

technologies and embodied emissions.

[15] The model is solved with standard perturbation techniques as implemented in `Dynare` (Adjemian et al., 2026). The computational details of the posterior simulation and the convergence diagnostics are reported in Appendix C.

Table 1: Italy's Steady-State Ratios

Description	Ratio	Value
Private consumption (% GDP)	C/Y	57.1
Total investment (% GDP)	I/Y	19.3
Imports (% GDP)	IMP/Y	25.7
Public consumption (% GDP)	G/Y	19.8
Public debt (% GDP)	$B/(4Y)$	124.4

Note: Values are computed as averages over the 1999Q1–2024Q4 sample.

complementary ways. First, we augment the model with two transitory COVID-19 shocks. A *forced-savings* shock, $\epsilon_{C,Covid}$, temporarily constrains private consumption from 2020Q1. A *labor-hoarding* shock, $\epsilon_{L,Covid}$, alters the labor intensity of production at the intensive margin and captures the wedge between hours worked and hours paid, reflecting the income-stabilization role of the Short-Time Work schemes adopted in Italy. Second, we let the variances of the affected shocks switch between a pre-COVID and a COVID regime, following the deterministic-heteroskedasticity approach of Lenza and Primiceri (2022) and Cardani et al. (2022). This keeps the linear-Gaussian structure of the state space intact, so the likelihood is still evaluated with a Kalman filter (but with time-varying innovation variances) while the 2020–21 observations enter the estimation without biasing the remaining parameters. Appendix A describes the regime-switching specification in detail.

3.2 Calibration of Macro Parameters

The steady-state ratios of the main economic aggregates to GDP are calibrated to match historical averages for Italy over the sample period. Table 1 reports the main economic ratios. The consumption-to-GDP and investment-to-GDP ratios are set to 57.1% and 19.3%, respectively, and imports to about 26%. We match the average share of public consumption close to 20%. The annual public-debt-to-GDP ratio is set to 124.4%, and the trade balance is zero in the steady state.

The remaining calibrated parameters are reported and discussed in detail in Appendix B. The calibration strategy follows closely the E-DSGE literature on the Italian and euro-area economies, from which the preference, depreciation, and adjustment-cost parameters take standard values. Three features of the calibration deserve mention here, because they shape the transmission of the policies analysed in Sections 4 and 5. First, the energy nests embed the technical limits to fuel switching in the short run: substitutability is low across fossil fuels and between fossil and renewable generation, while it is high across renewable technologies. Second, the factor shares in electricity generation match the observed composition of the Italian power supply, based on 2019–2024 averages from Terna and Eurostat data (Terna, 2026; Eurostat, 2026a). Third, sizeable price, wage, and investment adjustment costs reproduce the slow dynamics of the Italian macro aggregates and are essential for capturing the transitional effects of carbon pricing and energy-price shocks.

3.3 Calibration of Household-Related Parameters

The household-consumption block is calibrated on microeconomic evidence from the 2023 wave of the Administrative Household Budget Survey (AD-HBS). The AD-HBS is a linked administrative-survey database that combines the detailed expenditure information of the Italian Household Budget Survey (HBS), collected by the National Institute of Statistics (ISTAT), with administrative records from the National Social Security Institute (INPS). The resulting dataset jointly records household consumption expenditure, labor income, pensions, public transfers, and a rich set of demographic and labor-market characteristics. Its repeated cross-sectional structure preserves the representativeness of the Italian resident population over time, which makes it well suited to studying how expenditure patterns differ across household groups (Aprea et al., 2023; Barberis et al., 2026).

In the model economy, as described in Section 2, Ricardian households have access to financial markets and can smooth expenditure over time; non-Ricardian households are liquidity-constrained and consume close to their current disposable income. As an empirical counterpart to this distinction, we take the first decile of the consumption distribution as the reference group for non-Ricardian households and deciles two to ten for Ricardian households. This mapping reflects the evidence that the expenditure-income elasticity is highest at the bottom of the Italian distribution, where liquidity constraints are tightest and the scope for consumption smoothing is most limited (Barberis et al., 2026).[16]

Under the steady-state normalization in which the relative prices of the bundle components equal one, the CES distribution parameters coincide with the corresponding expenditure shares. We therefore calibrate the parameters in equations (20)–(21) directly from the observed expenditure composition in the AD-HBS.

Table 2 reports the resulting calibration. For the overall sample, non-energy goods account for 89.8% of total consumption expenditure, leaving an energy share of 10.2%. Within the energy bundle, refined fuel is the largest component (45.7%), followed by gas (29.4%) and electricity, which takes the residual share (24.9%).

[16] The decile used to *characterize* the non-Ricardian expenditure basket should not be confused with the *share* of non-Ricardian households in the model, $1 - s_R$, which is estimated separately (Section 3.4). We use the first decile because it most cleanly isolates the expenditure pattern of liquidity-constrained households, whose basket is the relevant object for the ETS 2 transmission channel; the population weight of this group is then disciplined by the macroeconomic data through the estimation of s_R, rather than imposed by the decile cutoff.

Table 2: Calibration of Household Consumption Shares from AD-HBS Data

	Overall sample	Non-Ricardian First decile	Ricardian Deciles 2–10
Upper nest: non-energy goods vs. energy			
$\alpha_{i,CY}$: non-energy goods share	0.8980	0.8694	0.8996
$1-\alpha_{i,CY}$: energy share	0.1020	0.1306	0.1004
Energy nest: refined fuel, gas, and electricity			
$\alpha_{i,ROIL}$: refined-fuel share	0.4573	0.3610	0.4620
$\alpha_{i,GAS}$: gas share	0.2939	0.2925	0.2941
$1-\alpha_{i,ROIL}-\alpha_{i,GAS}$: electricity share	0.2488	0.3465	0.2439

Notes: Authors' calculations on the 2023 AD-HBS data. Non-Ricardian households are proxied by the first decile of the consumption distribution, Ricardian households by deciles two to ten. The electricity share is the residual within the energy CES bundle.

The composition of expenditure, however, differs markedly across household types. Non-Ricardian households spend a smaller fraction of total expenditure on non-energy goods and therefore a larger fraction on energy: their energy share is 13.06%, against 10.04% for Ricardian households. The internal composition of the energy bundle also differs: the refined-fuel share is lower among non-Ricardian households, while the residual electricity share is considerably higher. These differences matter for the transmission of ETS 2, which raises the price of refined fuel and gas but not of electricity.

These type-specific shares introduce an empirically grounded source of heterogeneity. A common increase in the carbon-inclusive prices of fuel and gas falls more heavily on the basket of non-Ricardian households, and this direct price channel compounds their limited ability to smooth consumption. It is therefore central to the model's assessment of the distributional consequences of ETS 2.

3.4 Posterior Estimation Results

This section presents the Bayesian estimates of selected structural parameters. Table 3 reports the prior distributions and posterior estimates of these parameters. The persistence and standard deviations of the shock processes are collected in Appendix D.

Specifically, Table 3 reports the priors and posteriors of eight key parameters governing household behavior, price rigidities, and production elasticities. The contrast between priors and posteriors shows how the data inform each estimate, while the posterior intervals when relatively tight point to strong identification.

Habit persistence for Ricardian households, h_R, is estimated at 0.89, well above the prior mean of 0.70. This implies strong consumption smoothing, consistent with

Table 3: Prior and Posterior Distributions for Selected Parameters

Description	Parameter	Distr.	Mean	Std.	Mode	10%	90%
Economic Parameters							
Habit persistence (Ricardian)	h_R	beta	0.70	0.05	0.89	0.87	0.92
Habit persistence (RoW)	h_{RoW}	beta	0.70	0.05	0.93	0.92	0.93
Share of Ricardians	s_R	beta	0.60	0.10	0.64	0.47	0.73
Elasticity of subst. (consumption)	θ_C	gamma	0.10	0.10	0.15	0.06	0.23
Elasticity of subst. (capital-labor)	θ_{VA}	gamma	0.60	0.10	0.51	0.40	0.62
Elasticity of subst. (K-L-energy)	θ_Y	gamma	0.30	0.10	1.41	1.40	1.42
Response to lagged interest rate	κ_r	beta	0.80	0.02	0.83	0.80	0.85
Response to inflation	κ_π	normal	1.50	0.25	1.32	1.25	1.37

medium-scale DSGE models for the Euro Area and Italy (e.g., Albonico et al., 2019; Acocella et al., 2020) and with the persistent consumption dynamics reported for Italy in Annicchiarico et al. (2017).

The share of Ricardian households, s_R, is estimated at 0.64, close to its prior mean, implying that roughly a third of households are liquidity-constrained. This is consistent with the limited access of a sizable fraction of Italian households to financial markets (see Annicchiarico et al., 2015), and it gives redistributive policies a substantial role in stabilizing income and consumption along the transition.

The elasticity of substitution between goods and energy in consumption, θ_C, is estimated at 0.15, a low value that confirms the rigidity of energy demand in the face of price changes. The capital–labor elasticity, $\theta_{VA} = 0.51$, indicates moderate input flexibility, in line with the empirical macro literature (e.g., Albonico et al., 2019). The elasticity between value added, electricity, and non-electric energy is estimated at $\theta_Y = 1.41$, well above its prior mean of 0.30: the data pull towards substantially more input substitutability at this outer nest than typically calibrated. Note that this outer-nest flexibility coexists with strong rigidities within the energy block itself (θ_C, θ_{C_F}, and the fossil nests), so that the transmission of carbon pricing continues to operate mainly through the cost channel rather than through rapid input reallocation.

For the monetary policy rule, the coefficient on the lagged interest rate, $\kappa_r = 0.83$, reflects the usual degree of interest-rate smoothing. The response to inflation, $\kappa_\pi = 1.32$, lies somewhat below the textbook Taylor value of 1.5 but still above unity. These values are broadly in line with estimated ECB reaction functions (Coenen et al., 2024).

3.5 Model Validation

We conclude this section by looking at how the estimated model performs. To this end, Table 4 compares the unconditional standard deviations of selected macroeconomic variables in the model with their empirical counterparts over 1999Q1–2024Q4. The comparison offers a check of the model's ability to reproduce the relative amplitude of Italian business-cycle fluctuations.

Table 4: Unconditional Standard Deviation

Variable	**Symbol**	**Model**	**Data**
Real GDP	$\sigma(y)$	2.69	2.10
Private consumption	$\sigma(c)$	1.92	2.15
Private investment	$\sigma(i)$	3.17	3.90
Public expenditure	$\sigma(g)$	1.07	1.00
Imports	$\sigma(imp)$	3.10	3.49
Employment (hours)	$\sigma(l)$	3.56	2.82
CO_2 emissions	$\sigma(z)$	5.04	4.98
Consumer price inflation	$\sigma(pc)$	0.78	0.63
Energy prices	$\sigma(penergy)$	4.34	3.23
EA demand	$\sigma(yea)$	2.06	1.75

Notes: Unconditional standard deviations (%) of the model variables, compared with their empirical counterparts over 1999Q1–2024Q4. Model moments are computed from the estimated model at the posterior mode. All series are expressed in the same units and transformations used in the estimation.

Overall, the model reproduces the observed volatilities of the main aggregates fairly well. Output volatility is somewhat overstated (2.69% vs. 2.10%) but stays within the range typical of medium-scale DSGE models for Italy (Bartocci and Pisani, 2013). Consumption volatility is captured reasonably well, if slightly underestimated (1.92% vs. 2.15%), in line with the model's habit formation and liquidity constraints for non-Ricardian households. Investment volatility is also close to the data (3.17% vs. 3.90%), while public consumption is matched almost exactly (1.07% vs. 1.00%).

Imports and employment are likewise well reproduced (3.10% vs. 3.49% and 3.56% vs. 2.82%), supporting the calibration of the demand block and the labor market. The model slightly overpredicts the volatility of CO_2 emissions (5.04% vs. 4.98%) and energy prices (4.34% vs. 3.23%), and inflation is marginally more volatile than in the data (0.78% vs. 0.63%), a gap that is acceptable given the moderate nominal rigidities implied by the Rotemberg price adjustment costs, and consistent with recent transition-oriented DSGE models (Coenen et al., 2024). Finally, euro-area external demand is reasonably well matched (2.06% vs. 1.75%).

4 Low-Carbon Transition Scenarios

This section examines the macroeconomic and distributional effects of two carbon-mitigation policies: a tightening and extension of the EU Emissions Trading System, and the introduction of a carbon border adjustment mechanism. Table 5 summarizes the two scenarios.[17]

Table 5: Policy Scenarios

Scenario	Policy description	Size
ETS	Gradual tightening of the EU-wide emissions caps under ETS 1 and ETS 2.	ETS 1 cap: -80% relative to the baseline path; ETS 2 cap: -35% relative to the baseline path.
CBAM	Introduction of a border levy on carbon-intensive imported intermediate goods, set by the gap between the domestic and the foreign carbon price.	Terminal carbon-price differential matching the terminal ETS 1 price increase under the first scenario; the foreign carbon price is held constant.

Notes: Both policies are phased in over 15 years (60 quarters) from $t = 1$. Revenues from ETS permits and from the CBAM levy accrue to the government and are not recycled to households or firms.

Three assumptions are common to both scenarios. First, policies are fully credible and perfectly anticipated: agents internalize the entire transition path from $t = 1$ and adjust their intertemporal decisions accordingly. Second, policies are phased in gradually over 15 years, so that the reported effects at year 15 correspond to full implementation. Third, revenues accrue to the government but are not returned to the private sector. This last assumption is necessary to isolate the effects of carbon pricing in the absence of compensatory fiscal measures. Section 5 relaxes it and examines four alternative uses of the revenues.

The scenarios pair a deterministic policy path with the stochastic environment inherited from estimation. In particular simulations are carried out under the assumption that energy markets remain subject to shocks whose persistence and volatility are

[17] The size of the ETS shocks should be interpreted as an intermediate policy ambition between the 2030 Fit for 55 framework and a full decarbonization path towards climate neutrality by 2050. The exercise is not designed to replicate mechanically the legal caps embedded in EU legislation. Rather, it considers a stylized and fiscally sterilized transition path that is more ambitious than the 2030 Fit for 55 benchmark, especially for ETS 1 sectors, but still short of a complete net-zero-emissions scenario.

those implied by the posterior (see Appendix D). To quantify the resulting uncertainty, we also report Bayesian Highest Posterior Density (HPD) intervals, which contain the most probable outcomes given the posterior and, unlike equal-tail bands, adapt to skewness and multimodality.[18]

4.1 GHG Reduction – ETS

We begin with a policy package consistent with the European Green Deal and the "Fit for 55" objectives: a simultaneous activation of the two arms of the EU Emissions Trading System, ETS 1 for energy-intensive industry and power generation, ETS 2 for household fuels and heating. The caps are set at the EU27 level; domestic emissions then decrease endogenously as the permit price rises to clear the European market. See equations (48) and (50). The policy therefore reaches the Italian economy through two channels: a cost-push on energy-intensive production, and a direct squeeze on household disposable income. We first discuss the effects on the key macroeconomic variables[19], then examine the corresponding distributional consequences across households.

Macroeconomic Effects Table 6 reports the effects at year 15, when the policy is fully phased in. The results point to a persistent contraction in economic activity, reflecting the simultaneous activation of both cost and demand channels. In particular, on the production side, the tighter ETS 1 cap raises the effective cost of carbon-intensive inputs. Intermediate-good producers and fossil-electricity firms cut energy use, raise abatement effort, and scale down output. The adjustment is expensive twice over: permits are needed for residual emissions, and the abatement process itself consumes resources and is difficult to modify. See equation (5). Abatement costs reach 0.20% of GDP at year 15. The burden is compounded by the rigidity of energy demand within the energy nests: the low elasticities governing the fossil components and the energy–goods margin in consumption leave firms and households little scope to substitute away from carbon-intensive inputs, even though the estimated outer-nest elasticity θ_Y allows some reallocation between energy and value added.

On the household side, ETS 2 raises the carbon-inclusive prices of transport fuel and heating gas and erodes real disposable income. Because the energy goods are poor substitutes for one another, households cannot switch to electricity or other alternatives. Consumption falls by 1.31% and GDP by 1.17%, and the weaker private

[18] HPD intervals are constructed from parameter uncertainty, excluding measurement-error noise in the observables. This yields posterior samples of each variable at each horizon, from which we extract the shortest interval containing 80% of the posterior mass.

[19] Appendix F presents the macroeconomic effects of the two separate scenarios (ETS1 and ETS2).

demand feeds back into firms' sales and labor demand, reinforcing the ETS 1 contraction.

The composition of the household response is revealing. The items directly covered by ETS 2 adjust most: transport fuel and household gas both fall by around 3.5%, with HPD intervals well below zero. Electricity, which the ETS 2 charge does not touch directly, falls by only 1.15% and reacts mainly through real income. The energy aggregate lies in between, at −1.50%, but with a wide interval spanning zero. As expected, the CES composite is sensitive to energy-market conditions and to relative prices within the bundle.

Labor-market outcomes follow the output decline. Hours fall by 0.77% and real wages by 1.58%, the latter reflecting weaker labor demand and a lower marginal product of labor. Labor productivity declines by 0.40%: higher energy and abatement costs reduce the efficiency with which capital and labor combine with energy services. Investment falls by 0.95% as expected returns in carbon-intensive activities deteriorate. Investments in renewables fall as well by 3.09%. This may seem counter-intuitive: carbon pricing raises the cost of fossil generation relative to renewables, and one would expect clean capacity to expand. However, the relative-price incentive is indeed present: renewable electricity contracts by 2.25% against 3.35% for fossil generation, so renewables do gain share, but the effect is swamped by a scale effect. Total electricity demand falls by 2.95%, and with it the derived demand for renewable capacity. Two features of the model account for the weakness of the substitution margin. First, fossil and renewable generation are poor substitutes, so a large relative-price movement buys little reallocation. Second, expanding renewable output requires accumulating technology-specific capital against adjustment costs, and does so with decreasing returns, since each technology combines capital with a fixed natural-resource endowment. Renewable investment then falls by more than renewable generation for the standard accelerator reason: the investment flow adjusts the capital stock and therefore overshoots its response.[20]

Energy-market uncertainty matters most for the electricity block. Total electricity use ranges from −5.30% to −0.60% and fossil electricity from −6.98% to 0.28%, while renewable electricity is tightly distributed around its mean, consistent with its insulation from short-run fossil-price movements and with the slow adjustment of installed capacity. The same mechanism explains the CPI response: modest on average (0.42%) but unambiguously positive, with an interval from 0.06% to 0.77%. Once weak de-

[20]Two caveats follow. The model holds the cost of renewable technologies fixed and abstracts from learning-by-doing, so it cannot capture the endogenous cheapening of clean capital that a sustained carbon price might induce. And the fixed resource endowments cap the scope for capacity expansion. The clean-investment response reported here should therefore be read as a lower bound: the model is informative about the short- to medium-run transition costs of carbon pricing, not about the long-run supply response of the renewable sector.

mand, price rigidities, and energy-price uncertainty are taken together, the policy does not deliver a large inflationary impulse.

The caps bind progressively, and permit prices rise accordingly: with supply fixed, the carbon price must climb until demand is consistent with the targeted path. At year 15 the ETS 1 price reaches roughly 179 euro per tonne of CO_2 and the ETS 2 price roughly 166, while permit revenues amount to 0.76% of GDP. Because these revenues are not recycled, they act as a fiscal leakage that reinforces the contractionary effect of the carbon wedges. Aggregate welfare falls by 0.28% in consumption-equivalent terms: the loss of consumption and real income more than offsets the mechanical utility gain from working less. That aggregate figure, however, conceals a good deal of heterogeneity across households.

Distributional Effects Table 7 splits the response by household type. The burden is not evenly shared. Non-Ricardian households lose more on every margin, consumption, disposable income, and welfare. The policy delivers the intended emission reductions, but its costs are regressive absent compensation.

Consumption falls by 1.09% for Ricardians against 2.11% for non-Ricardians, and the welfare gap is sharper still: 0.22% versus 0.38% in consumption-equivalent terms, a loss roughly three-quarters larger. Two forces combine here. First, Ricardian households can smooth the temporary loss of real income through saving and asset holdings, whereas non-Ricardians consume their current disposable income period by period, so any rise in the cost of essentials or fall in labor income passes straight into expenditure. Disposable income itself falls by 1.88% for Ricardians and 2.35% for non-Ricardians. This gap is much narrower than the gap in consumption, which is precisely the point: the difference in outcomes is driven less by income than by the inability to smooth. Second, non-Ricardian households start from a more energy-intensive basket, so a given increase in carbon-inclusive energy prices bites harder on their purchasing power.

The breakdown by component is informative. The gap is visible in the final-good component (-1.09% versus -2.11%) and in the energy aggregate (-1.27% versus -2.21%), but it is largest for the goods directly exposed to ETS 2: transport fuel and gas fall by 3.20% for Ricardians and 4.31% for non-Ricardians. Even electricity, which carries no ETS 2 charge, contracts by 0.77% for Ricardians against 1.88% for non-Ricardians.

Energy-market uncertainty compounds the asymmetry. The non-Ricardian intervals are not merely wider; they sit in a systematically more adverse region. For total consumption, final-good consumption, energy consumption, transport fuel, gas, electricity, and disposable income alike, the non-Ricardian intervals lie entirely below zero. Even favourable energy-market realizations, in other words, leave liquidity-

Table 6: The Macroeconomic Impact of ETS Implementation at Year 15 under Energy-Market Uncertainty

Variable	Mean	Energy HPD
GDP – Y	-1.170	[-1.357, -0.983]
Consumption – C	-1.306	[-1.609, -1.004]
Consumption – Final Good C_Y	-1.295	[-1.553, -1.038]
Consumption – Energy C_F	-1.495	[-3.296, 0.307]
Consumption – *Transport* $ROIL$	-3.449	[-4.995, -1.903]
Consumption – *Electricity* EL_C	-1.152	[-2.590, 0.286]
Consumption – *Gas* GAS_C	-3.498	[-5.003, -1.993]
Hours – L	-0.773	[-0.920, -0.627]
Welfare – W	-0.284	[-0.289, -0.280]
Wages – w	-1.578	[-1.649, -1.507]
Labor Productivity – Y/L	-0.397	[-0.570, -0.224]
Investment – I	-0.947	[-1.014, -0.880]
Investment *Renewables* – $IRES$	-3.091	[-3.613, -2.569]
Price – CPI	0.415	[0.058, 0.771]
Price markup – Intermediate-good sector μ^p	1.942	[1.855, 2.029]
Electricity Price – P_{EL}	0.608	[-0.999, 2.215]
Electricity – EL	-2.950	[-5.301, -0.600]
Electricity *Fossil* – $ELFOS$	-3.349	[-6.979, 0.282]
Electricity *Renewables* – $ELRES$	-2.253	[-2.453, -2.053]
Electricity Imported – % GDP – $ELFY$	-0.013	[-0.021, -0.005]
Trade Balance – % GDP – TB_Y	-0.223	[-0.321, -0.126]
Abatement Costs – % GDP – CA_Y	0.202	[0.202, 0.203]
Revenues ETS – % GDP – REV_Y^{ETS}	0.755	[0.754, 0.757]
ETS Price €/tCO_2 – P_Z^{ETS}	178.590	[178.554, 178.626]
ETS 2 Price €/tCO_2 – P_Z^{ETS2}	165.818	[165.601, 166.035]

Notes: Values are expressed as percentage deviations relative to the steady state at the time in which the mitigation is fully implemented (15 years), except for variables reported in % GDP, which are displayed in percentage points. The *Energy HPD* column includes only energy–market uncertainty. *HPD* denotes the shortest credible interval containing 80% of the posterior mass. Welfare HPDs are signed to match the mean (negative CEV implies a loss).

constrained households with an unambiguous loss. Energy-market uncertainty is thus not only a source of macroeconomic risk but of distributional risk: what varies across households is not just the average cost of the transition but the capacity to absorb adverse events.

The concentration of the adjustment in gas and transport fuel deserves emphasis. These goods are hard to replace quickly, especially for households in energy-inefficient dwellings, on gas-based heating, or without access to public transport and low-carbon mobility. The transition can therefore widen existing gaps between households able to invest in efficiency, cleaner heating, or alternative mobility and those who are not. The relevant dimension of vulnerability is not only current income, but access to assets, housing quality, location, and the ability to finance green investment.

Table 7: The Distributional Impact of ETS Implementation at Year 15 under Energy-Market Uncertainty

Variable	Ricardian	Energy HPD	Non-Ricardian	Energy HPD
Welfare – W	-0.218	[-0.221, -0.214]	-0.381	[-0.386, -0.376]
Consumption – C	-1.094	[-1.353, -0.835]	-2.112	[-2.637, -1.587]
Consumption – Final Good C_Y	-1.089	[-1.312, -0.865]	-2.107	[-2.574, -1.640]
Consumption – Energy C_F	-1.265	[-3.129, 0.599]	-2.205	[-3.816, -0.593]
Consumption – Transport $ROIL$	-3.200	[-4.951, -1.453]	-4.311	[-5.149, -3.475]
Consumption – Electricity EL_C	-0.774	[-2.525, 0.978]	-1.880	[-2.719, -1.041]
Consumption – Gas GAS_C	-3.204	[-4.955, -1.454]	-4.309	[-5.147, -3.472]
Disposable Income – $DISPY$	-1.878	[-2.024, -1.731]	-2.352	[-2.518, -2.186]

Notes: Values are expressed as percentage deviations relative to the steady state at the time in which the mitigation is fully implemented (15 years). "HPD" denotes the shortest credible interval containing 80% of the posterior mass. The Energy HPD columns vary only energy–market uncertainty. Welfare HPDs are signed to match the mean (negative CEV implies a loss).

4.2 Carbon Border Adjustment Mechanism

We now introduce a border levy on carbon-intensive imported intermediate goods, $IMP_{CBAM,t}$. The effective tariff is set by the positive gap between the domestic and the foreign carbon price, scaled by the embodied-carbon and regulatory-coverage parameter ϕ_e (see equation (51)). The foreign carbon price is held constant, and the terminal differential is calibrated to match the ETS 1 price increase generated by the previous scenario. Domestic producers therefore face a progressively larger carbon-cost advantage over foreign competitors subject to little or no carbon pricing.[21]

The experiment is designed to isolate the border channel. The domestic cap is kept unchanged, so the domestic carbon price does not rise, domestic firms face no additional abatement requirement, and the carbon-inclusive prices of household fuel and gas are untouched. What the levy does is raise the relative price of covered imports, which propagates through production costs, pricing decisions, and the final-good price index. Households are reached only indirectly through consumer prices, labor income, and distributed profits.

Macroeconomic effects Table 8 reports the effects at year 15. Clearly, the picture is very different from the ETS scenario. The CBAM is a relative-price shock on a narrow set of imported inputs, and its footprint is correspondingly small, unlike the ETS package, which raised the domestic carbon cost of both production and household energy use.

The clearest effect is on the covered imports themselves, which fall by 1.46% with an interval well away from zero. Final-good producers substitute away from CBAM-covered inputs towards domestic intermediates and, to a lesser extent, towards imports outside the perimeter of the policy. This is the main quantitative effect of the policy in the model.

The substitution produces a small expansion in domestic activity: GDP rises by 0.07%, hours by 0.06%, investment by 0.05%. These magnitudes are negligible and their intervals include zero, so the expansion is not robust across energy-market realizations. The sign, however, is informative. By raising the cost of covered foreign inputs while leaving the domestic permit price alone, the levy improves the relative standing of domestic producers in the home market. Abatement costs remain at zero throughout: nothing in this scenario obliges domestic firms to abate.

Price and household effects are also contained. The CPI rises by 0.17% and the intermediate-good markup by 0.03%, both with intervals spanning zero. Pass-through is partial because covered imports represent a limited share of total inputs and because producers can substitute towards domestic and uncovered foreign alternatives. Consumption falls by 0.14%, with the individual energy components showing only small mean declines and wide intervals. Compared with the combined ETS 1– ETS 2 package, the aggregate inflationary impulse is far weaker.

The energy block barely moves. Electricity use rises by 0.09%, with fossil and renewable generation rising by similar amounts and with wide intervals. These movements should not be read as the CBAM promoting either fossil or clean energy; rather, these changes simply track the small increase in domestic production. The policy

[21] For a possible alternative design of this policy without requiring any knowledge about foreign carbon intensities of production see Campolmi et al. (2024).

leaves the domestic carbon-price path unchanged, so none of the fossil-to-clean substitution that characterizes the ETS scenario is triggered here. The external balance is essentially flat, confirming that the mechanism reallocates the composition of inputs rather than shifting the aggregate trade position.

The border tariff reaches 22.6 euro per tonne at year 15, with a very narrow interval: the announced carbon-price differential is deterministic and dominates energy-market noise in determining the levy. Revenues amount to 0.20% of GDP. As before they are not recycled, and this fiscal leakage, together with the modest consumption decline and the higher price index, is why welfare falls by 0.05% in consumption-equivalent terms despite output rising. A positive GDP response need not imply a welfare gain: the policy shifts the composition of demand towards domestic production, but it also raises input costs and transfers resources to the public sector.

Table 8: The Macroeconomic Impact of CBAM Implementation at Year 15 under Energy-Market Uncertainty

Variable	Mean	Energy HPD
GDP – Y	0.066	[-0.121, 0.253]
Consumption – C	-0.143	[-0.445, 0.160]
Consumption – Final Good C_Y	-0.144	[-0.401, 0.113]
Consumption – Energy C_F	-0.115	[-1.916, 1.686]
Consumption – $Transport\ ROIL$	-0.119	[-1.665, 1.427]
Consumption – $Electricity\ EL_C$	-0.105	[-1.544, 1.333]
Consumption – $Gas\ GAS_C$	-0.115	[-1.620, 1.391]
Hours – L	0.063	[-0.083, 0.210]
Welfare – W	-0.048	[-0.053, -0.044]
Wages – w	0.002	[-0.069, 0.073]
Labor Productivity – Y/L	0.003	[-0.170, 0.176]
Investment – I	0.046	[-0.021, 0.113]
Investment $Renewables$ – $IRES$	0.097	[-0.424, 0.619]
Price – CPI	0.166	[-0.191, 0.522]
Price markup – Intermediate-good sector μ^p	0.032	[-0.055, 0.119]
Electricity Price – P_{EL}	0.017	[-1.590, 1.624]
Electricity – EL	0.088	[-2.262, 2.438]
Electricity $Fossil$ – $ELFOS$	0.094	[-3.537, 3.724]
Electricity $Renewables$ – $ELRES$	0.078	[-0.122, 0.278]
CBAM Import – IMP^{CBAM}	-1.456	[-1.593, -1.319]
Trade Balance – % GDP – TB_Y	-0.006	[-0.104, 0.091]
Abatement Costs – % GDP – CA_Y	0.000	[0.000, 0.000]
Revenues CBAM – % GDP – REV_Y^{CBAM}	0.196	[0.196, 0.196]
Carbon CBAM Tariff €/tCO_2 – P_Z^{CBAM}	22.592	[22.583, 22.601]

Notes: Values are expressed as percentage deviations relative to the steady state at the time in which the policy is fully implemented (15 years), except for variables reported in % GDP, which are displayed in percentage points. The *Energy HPD* column includes only energy–market uncertainty. *HPD* denotes the shortest credible interval containing 80% of the posterior mass. Welfare HPDs are signed to match the mean (negative CEV implies a loss).

Distributional effects Table 9 splits the response by household type. The ranking is reversed relative to the ETS scenario. There, non-Ricardian households bore the larger burden. Here, Ricardian households lose more: welfare falls by 0.06% against 0.03%, and consumption by 0.16% against 0.07%. The aggregate effects are small, but they are not shared symmetrically.

The reversal of the distributional effects follows from where the two instruments bite. ETS 2 acts directly on household energy expenditure, which is why it is regressive: liquidity-constrained households have the more energy-intensive basket and the lesser capacity to smooth. The CBAM applies to imported intermediate goods and leaves the prices of transport fuel, heating gas, and electricity untouched. That channel is simply absent in this policy experiment.

What remains is a factor-income channel, and it runs the other way. Ricardian households own the capital, hold the financial assets, and receive distributed profits, so they absorb the squeeze on firms' margins caused by dearer covered imports. Import substitution supports domestic output, but it does so while raising input costs and compressing profitability in the sectors linked to the covered bundle. Ricardian disposable income falls by 0.18% as a result.[22] Non-Ricardian households, by contrast, live off current labor income. Since hours rise slightly and wages are broadly unchanged, their disposable income edges up by 0.07%. They are neither exposed to a direct energy-price increase nor to the profit squeeze, and the modest expansion in labor demand works in their favor.

The consumption decomposition is consistent with this reading: Ricardian energy consumption falls by 0.14% against 0.04% for non-Ricardians, with the individual components clustered tightly around those values. All are an order of magnitude smaller than under ETS 2, and all have intervals spanning zero.

Finally, energy-market uncertainty affects the dispersion of these responses but not the welfare ranking: the welfare intervals lie entirely below zero for both types, with the Ricardian interval in the more adverse region, while the consumption and income intervals generally include zero. That is what one would expect from a policy transmitted through a narrow set of imported inputs rather than through a broad and persistent increase in household energy prices.

[22] Hübler et al. (2024) obtain a related result: border carbon pricing can raise the relative income loss of higher-income households while being comparatively more favorable to lower-income groups.

Table 9: The Distributional Impact of CBAM Implementation at Year 15 under Energy-Market Uncertainty

Variable	Ricardian	Energy HPD	Non-Ricardian	Energy HPD
Welfare – W	-0.058	[-0.062, -0.054]	-0.034	[-0.039, -0.028]
Consumption – C	-0.163	[-0.422, 0.096]	-0.066	[-0.591, 0.460]
Consumption – Final Good C_Y	-0.164	[-0.387, 0.060]	-0.067	[-0.534, 0.400]
Consumption – Energy C_F	-0.139	[-2.003, 1.726]	-0.042	[-1.654, 1.569]
Consumption – Transport $ROIL$	-0.139	[-1.890, 1.612]	-0.047	[-0.881, 0.793]
Consumption – Electricity EL_C	-0.138	[-1.890, 1.614]	-0.042	[-0.881, 0.798]
Consumption – Gas GAS_C	-0.137	[-1.888, 1.612]	-0.043	[-0.882, 0.795]
Disposable Income – $DISPY$	-0.177	[-0.323, -0.030]	0.065	[-0.101, 0.231]

Notes: Values are expressed as percentage deviations relative to the steady state at the time in which the policy is fully implemented (15 years). "HPD" denotes the shortest credible interval containing 80% of the posterior mass. The Energy HPD columns vary only energy–market uncertainty. Welfare HPDs are signed to match the mean (negative CEV implies a loss).

5 Mitigation Policies with Revenue Recycling

In the previous experiments, the revenues from carbon pricing simply accumulated in the public budget. That assumption was useful, since it isolates the effects of the carbon wedges themselves, but it is also the least realistic feature of the exercise, and it matters for the results: the leakage of resources from the private sector deepens both the contraction and its regressive incidence.

The experiment differs from the previous ones in a second respect: ETS and CBAM are implemented jointly, so that the revenue pool being recycled is the combined one. The "Baseline" column of Table 10 therefore reports the joint package without recycling and serves as the reference point throughout this section.

We consider four uses of the revenues, chosen to span the margins a government might plausibly target. Cutting employers' social security contributions lowers the labor-cost wedge and works through firms' labor demand. Cutting workers' contributions raises net labor income and works through household budgets. Lowering VAT compresses the consumer-price wedge and works through purchasing power. The fourth scheme is different in kind: rather than compensating current income, it channels the revenues into renewable-energy investment, targeting the composition of the capital stock and the energy supply. The comparison thus sets short-run stabilization and distributional protection against the longer-run transformation of the energy system.[23]

5.1 Macroeconomic Effects

Table 10 compares the macroeconomic effects of the joint ETS and CBAM package under alternative uses of the associated revenues. It comes as no surprise that every scheme improves on the baseline: each replaces a pure fiscal leakage with either a lower distortionary wedge or public support for clean capital. What matters is that the margin chosen shapes the outcome, and the four schemes are not close substitutes.

Cutting employers' contributions is the most direct support to firms. Lowering the effective cost of labor lifts GDP from −1.10% to −0.07% and turns hours positive (+0.40%), while the real wage decline shrinks from −1.58% to −0.21% and investment nearly stabilizes. Consumption, however, remains 0.50% below steady state: nothing in the scheme offsets the higher carbon-inclusive prices of transport fuel and gas, whose consumption stays around −2.6%.

Cutting workers' contributions works from the other side. It leaves firms' labor costs and the gross real wage close to baseline, but raises net labor income and the return to supplying labor. This is the best of the three tax-based schemes for household expenditure: consumption turns marginally positive (+0.09%) and GDP is all but stabilized at −0.04%, with hours up 0.40%. The ETS 2 relative-price wedge survives, though fuel and gas consumption still fall by around 2%. The scheme compensates the income loss without blunting the incentive to use less fossil energy, which is arguably what one wants from it.

VAT recycling runs through the price index. It is the only scheme that turns the CPI negative, from +0.58% in the baseline to −0.57%. But it does less for activity: GDP still falls 0.63% and hours 0.20%, because a VAT cut neither reduces firms' marginal labor cost nor raises the net return to work. And a lower average price level does not undo carbon-induced movements in relative prices: electricity prices stay positive at 0.79% and fuel and gas consumption still contract by roughly 3%.

Recycling into renewable investment produces an adjustment of a different character altogether. Clean investment rises by 48.7% against a baseline decline of nearly 3%, renewable generation by 34.7%, electricity prices fall by 14.2%, and total electricity

[23] In each recycling scheme a single fiscal instrument is made endogenous and adjusts period by period so that the recycled revenue equals the combined ETS and CBAM proceeds, while all other instruments are held at their baseline paths. Under the employers' contribution cut the endogenous instrument is $\tau_{f,t}^{W_{L^R}}$; under the workers' contribution cut it is $\tau_{h,t}^{W_{L^R}}$; under VAT recycling it is the consumption-tax rate τ_t^C; and under renewable recycling it is the investment tax credit on renewable-energy capital, $tcrk_{RES,t}$. In all four cases the lump-sum tax TAX_t, which is normally the residual instrument stabilizing public debt, is held fixed for the duration of the experiment, so that the carbon revenues are channelled through the chosen instrument rather than absorbed automatically into the budget.

Table 10: The Macroeconomic Impact of the Joint ETS and CBAM Implementation at Year 15 under Alternative Revenue-Recycling Schemes

	No recycling	Revenue recycling			
Variable	Baseline	Employers' SCC	Workers' SCC	VAT	Renewables
GDP – Y	-1.104	-0.070	-0.044	-0.630	-0.195
Consumption – C	-1.449	-0.501	0.085	-0.752	-0.004
Consumption – Final Good C_Y	-1.439	-0.500	0.079	-0.744	0.018
Consumption – Energy C_F	-1.610	-0.632	0.002	-1.045	-0.287
Consumption – *Transport* $ROIL$	-3.567	-2.594	-1.978	-3.067	-2.126
Consumption – *Electricity* EL_C	-1.257	-0.124	0.630	-0.570	-0.120
Consumption – *Gas* GAS_C	-3.612	-2.564	-1.893	-3.060	-2.248
Hours – L	-0.711	0.395	0.395	-0.203	-1.480
Welfare – W	-0.332	-0.208	-0.082	-0.224	0.244
Wages – w	-1.577	-0.212	-1.620	-1.601	-0.397
Labor Productivity – Y/L	-0.394	-0.465	-0.439	-0.427	1.285
Investment – I	-0.905	-0.204	-0.190	-0.510	-1.502
Investment *Renewables* – $IRES$	-2.995	-2.364	-2.044	-2.680	48.660
Price – CPI	0.580	0.344	0.365	-0.573	0.115
Price markup – Intermediate-good sector μ^p	1.974	1.578	1.640	1.973	1.194
Electricity Price – P_{EL}	0.625	0.532	0.508	0.791	-14.167
Electricity – EL	-2.863	-2.338	-2.141	-2.625	18.926
Electricity *Fossil* – $ELFOS$	-3.255	-2.701	-2.493	-3.005	9.906
Electricity *Renewables* – $ELRES$	-2.176	-1.702	-1.526	-1.960	34.725
Electricity Imported – % Y – $ELFY$	-0.013	-0.014	-0.013	-0.013	-0.080
Trade Balance – % Y – TBY	-0.229	-0.012	-0.233	-0.251	-0.283
Abatement Costs – % Y – CA_Y	0.202	0.203	0.203	0.202	0.204

Notes: Values are expressed as percentage deviations relative to the steady state at the time in which the joint ETS and CBAM policy is fully implemented (15 years). The baseline scenario assumes that policy revenues are not recycled. Under the alternative scenarios, revenues are used to reduce employers' social security contributions (Employers' SCC), workers' social security contributions (Workers' SCC), VAT, or are allocated to renewable-energy investment (Renewables).

use rises by 18.9%. Cheaper electricity roughly holds consumption at steady state and lifts welfare by 0.24%. This is the only recycling policy scheme delivering an aggregate welfare gain. It is worth pausing on why this scheme succeeds where carbon pricing alone did not: Section 4 showed that the ETS package shrank renewable investment, because the collapse in total electricity demand swamped the relative-price incentive. Subsidizing clean capital directly bypasses that negative scale effect. However, incentivizing clean capital presents two side-effects. First, aggregate investment falls by 1.50%, that is more than in the baseline, so the expansion of clean capital crowds out investment elsewhere. Second, and more strikingly, fossil generation *rises* by 9.9%. This is not a failure of the model but a rebound effect: the renewable expansion lowers electricity prices, cheaper electricity raises total demand by 18.9%, and with fossil and renewable generation poor substitutes in the short run, existing fossil capacity is called on to meet part of that extra demand. Since the ETS 1 cap still binds, the emissions consequence is contained, but the episode is a useful reminder that supply-side support for renewables, absent a tightening cap, can raise the use of fossil inputs rather than displace it.

The labor and productivity numbers should be read with care. Hours fall by 1.48% while GDP falls by only 0.20%, so measured labor productivity rises by 1.29%. This is not a technology improvement: it is an arithmetic consequence of an adjustment that substitutes capital for labor, with output contracting far less than labor input.

The picture that emerges is a trade-off. The two contribution cuts are the best stabilizers of output, employment, and consumption, with the workers' cut strongest for household expenditure. VAT recycling is the instrument for containing inflation but the weakest for economic activity. Renewable recycling delivers the largest structural change and the only aggregate welfare gain, but does so through a capital-intensive adjustment that weakens labor demand and crowds out other investment.

5.2 Distributional effects

Tables 11 and 12 show that revenue recycling substantially changes not only the aggregate welfare cost of the joint ETS and CBAM package, but also its incidence across household types. In the no-recycling benchmark the burden sits with non-Ricardian households, as before: consumption -2.18% against -1.26% for Ricardians, with a correspondingly larger welfare loss. The four schemes redistribute that burden in quite different ways.

Cutting employers' contributions transmits to non-Ricardians through the labor market. The expansion in labor demand raises their disposable income by 0.18%, pushes consumption marginally above steady state, and cuts their welfare loss from -0.41% to -0.07%. Because they consume their disposable income period by period, a stronger labor market reaches them fast.

Cutting workers' contributions is stronger still, and is the most equalizing of the four. Non-Ricardian disposable income rises by 1.69%, consumption by 1.67%, and welfare turns positive at $+0.29\%$. Direct support to net wages is worth most precisely to households that cannot borrow or save their way across a temporary income shock. Fuel and gas consumption still falls, as the ETS 2 wedge is untouched.

Both contribution cuts, however, leave Ricardian *welfare* slightly worse than the baseline: -0.30% and -0.34% against -0.28%, even though their consumption and disposable income both improve markedly. The apparent contradiction dissolves once one recalls that welfare in (15) counts leisure as well as consumption. Both schemes stimulate labor supply, and the extra disutility of work outweighs the consumption gain for households that were already smoothing intertemporally and therefore value the additional current income less. This is a property of the welfare measure rather than an anomaly, but it does mean that the schemes that best stabilize the aggregates are not the ones Ricardians would choose.

VAT recycling compensates more broadly but less precisely. It lifts consumption for both types from -1.26% to -0.80% for Ricardians and from -2.18% to -0.56% for non-Ricardians, with the larger relative gain going to the liquidity-constrained, whose budget constraint is tighter and whose marginal propensity to consume is higher. But the carbon component of fuel and gas prices remains, so consumption of those goods stays well below baseline for both groups. Non-Ricardian welfare improves markedly while staying negative; Ricardian welfare is broadly unchanged.

The renewable scheme splits the two groups most sharply. Ricardians gain: welfare $+0.50\%$, consumption $+0.55\%$, electricity consumption $+0.82\%$, supported by cheaper electricity and by their ownership of the clean capital being accumulated. Non-Ricardians do not. They are exposed to the weaker labor demand that the capital-intensive adjustment brings: disposable income -1.88% and their consumption stays close to its baseline contraction at -2.11%. Cheaper electricity is not enough to compensate. This is the sharpest illustration in the paper of a general point: a scheme can raise aggregate welfare, accelerate the transformation of the electricity system, and still leave the constrained group no better off, when the returns to the clean capital accrue to those who own it.

The policy trade-off is therefore fairly stark. Workers' contribution cuts protect liquidity-constrained households best, because they act directly on current disposable income. Employers' cuts stabilize employment and output, with less evenly shared welfare gains. VAT recycling lowers the general price wedge but leaves carbon-induced relative prices intact. And renewable recycling, the only scheme with an aggregate welfare gain, concentrates that gain among financially unconstrained households.

Table 11: Distributional Effects of the Joint ETS and CBAM Policy at Year 15: Ricardian Households

	No recycling	Revenue recycling			
Variable	Baseline	Employers' SCC	Workers' SCC	VAT	Renewables
Welfare – W_R	-0.275	-0.303	-0.338	-0.292	0.496
Consumption – C^R	-1.256	-0.660	-0.333	-0.803	0.552
Consumption – Final Good C_Y^R	-1.252	-0.655	-0.328	-0.794	0.558
Consumption – Energy C_F^R	-1.403	-0.838	-0.507	-1.125	0.346
Consumption – *Transport* $ROIL^R$	-3.343	-2.744	-2.405	-3.102	-1.517
Consumption – *Electricity* EL_C^R	-0.911	-0.355	-0.026	-0.624	0.818
Consumption – *Gas* GAS_C^R	-3.343	-2.744	-2.405	-3.102	-1.517
Disposable Income – $DISPY^R$	-2.055	-0.794	-0.262	-1.655	0.056

Notes: Values are expressed as percentage deviations relative to the steady state at the time in which the joint ETS and CBAM policy is fully implemented (15 years). The baseline scenario assumes that ETS and CBAM revenues are not recycled. Under the alternative scenarios, revenues are used to reduce employers' social security contributions (Employers' SCC), workers' social security contributions (Workers' SCC), VAT, or are allocated to renewable-energy investment (Renewables).

Table 12: Distributional Effects of the Joint ETS and CBAM Policy at Year 15: Non-Ricardian Households

	No recycling	Revenue recycling			
Variable	Baseline	Employers' SCC	Workers' SCC	VAT	Renewables
Welfare – W_{NR}	-0.414	-0.069	0.291	-0.126	-0.122
Consumption – C^{NR}	-2.178	0.102	1.671	-0.560	-2.108
Consumption – Final Good C_Y^{NR}	-2.174	0.108	1.676	-0.547	-2.100
Consumption – Energy C_F^{NR}	-2.247	0.002	1.574	-0.798	-2.237
Consumption – *Transport* $ROIL^{NR}$	-4.353	-2.069	-0.486	-2.945	-4.260
Consumption – *Electricity* EL_C^{NR}	-1.922	0.321	1.892	-0.467	-1.925
Consumption – *Gas* GAS_C^{NR}	-4.353	-2.069	-0.486	-2.945	-4.260
Disposable Income – $DISPY^{NR}$	-2.287	0.183	1.693	-1.804	-1.877

Notes: Values are expressed as percentage deviations relative to the steady state at the time in which the joint ETS and CBAM policy is fully implemented (15 years). The baseline scenario assumes that ETS and CBAM revenues are not recycled. Under the alternative scenarios, revenues are used to reduce employers' social security contributions (Employers' SCC), workers' social security contributions (Workers' SCC), VAT, or are allocated to renewable-energy investment (Renewables).

6 Conclusions

This paper develops and estimates a large-scale environmental dynamic stochastic general equilibrium model for the Italian economy, combining a detailed energy sector with household heterogeneity in an open-economy setting. The model is estimated with Bayesian techniques on quarterly data over 1999Q1–2024Q4, allowing for time-varying volatility to accommodate the pandemic period. The model replicates the main features of the Italian business cycle and captures the relative volatility of macroeconomic and energy variables. Its dual-cap structure, with ETS 1 for producers and ETS 2 for households, makes it possible to trace the incidence of carbon pricing across financially constrained and unconstrained households, an area still relatively underexplored in the literature.

Three findings emerge. First, tightening the two ETS caps delivers the intended abatement at a persistent cost: after fifteen years, output and consumption remain over one percent below baseline, and the cost is regressive. Liquidity-constrained households, whose baskets are more energy-intensive, cut consumption by roughly twice as much as unconstrained ones. Second, the carbon border adjustment mechanism reverses this incidence. Because it taxes imported intermediates rather than household energy, its modest costs fall on asset-owning households through the compression of firms' margins, while liquidity-constrained households are largely spared. Third, the use of the revenues matters more than the choice between instruments. Recycling through cuts in workers' social security contributions nearly eliminates the aggregate output loss and turns the welfare of liquidity-constrained households positive. Recycling into renewable investment is the only scheme that raises aggregate welfare and the only one that transforms the electricity sector, but its gains accrue to the owners of clean capital, leaving the constrained group of households no better off. Therefore, no single scheme is both efficient and equitable.

These results should be read as conservative. The model holds the cost of clean technologies fixed, abstracts from learning-by-doing, and keeps the elasticities of substitution constant over the transition, so it allows neither the endogenous cheapening of renewable capital nor the gradual reallocation of inputs that a sustained carbon price would in practice induce. The macroeconomic costs reported here, and the contraction in renewable investment in particular, are therefore likely to overstate the burden that a more flexible technology would impose.

The policy implication of our analysis is straightforward. The regressivity of carbon pricing is a consequence of design choices, not an intrinsic feature: the same revenue flow, returned through different channels, produces very different distributions of the burden. For a country like Italy, where energy poverty is significant and a large share of households is liquidity-constrained, the compensation scheme is not an accessory to the carbon-pricing package. It should be a part of the package that determines its social sustainability.

Future work could extend the model in several directions: by endogenizing technological progress and learning in green investment, which would likely soften the contraction in renewable investment that carbon pricing alone produces in our framework; by incorporating uncertainty in climate damages and policy credibility; and by evaluating optimal policy mixes under welfare criteria that explicitly account for equity and intertemporal trade-offs.

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A The Modeling of the COVID-19 Shock

The 2020–21 pandemic produced output and consumption swings that are extraordinary by the standards of the estimation sample. Treating these quarters as ordinary draws from the pre-pandemic shock distribution would distort the estimated persistence and volatility of the structural shocks, as the filter would attribute an implausibly large innovation to every disturbance in order to match the data. We address this in two steps. First, we add two *transitory* structural shocks that capture the specific economic content of the pandemic episode: a forced contraction of private spending and a wedge between hours worked and hours paid. Second, we allow the variance of the COVID related disturbances to shift across regimes, following the deterministic-heteroskedasticity approach of Lenza and Primiceri (2022) and its application to an estimated euro-area model in Cardani et al. (2022). The two steps are complementary: the structural shocks give the episode an economic interpretation, while the regime-switching variance prevents the exceptional 2020–21 observations from contaminating the inference on the remaining parameters.

A.1 The Forced-Savings Shock

The first disturbance captures the abrupt, lockdown-induced fall in private consumption that was not driven by the usual intertemporal motives. It enters the instantaneous utility of household $i \in \{R, NR\}$ directly, as in equation (15):

$$U_t^i = \log\left(C_t^i \, e^{\epsilon_{C,Covid,t}} - h_C^i \, \bar{C}_{t-1}^i\right) - \frac{\omega_L}{1+\nu_L} \, (L_t^i)^{1+\nu_L}. \tag{A.1}$$

The shock $\epsilon_{C,Covid,t}$ scales current consumption inside the felicity function. A negative realization lowers the marginal utility of present consumption and therefore acts as a temporary, exogenous constraint on spending, mimicking the mechanical demand compression of the lockdown period.[24] The shock applies symmetrically to both household types, so that the pandemic compresses Ricardian and non-Ricardian consumption alike, while the differential persistence of their responses still arises endogenously from their distinct budget constraints.

A.2 The Labor-Hoarding Shock

The second disturbance addresses a feature specific to the European pandemic labor market: large-scale short-time-work (STW) schemes kept workers formally employed

[24]Because the term multiplies C_t^i but not the habit stock $h_C^i \bar{C}_{t-1}^i$, the disturbance is deliberately kept outside the habit-persistence mechanism. This is what makes it *transitory*: it does not propagate through the consumption Euler equation in the way a standard preference shock would, and it leaves no lasting imprint on the habit reference level once the pandemic regime ends.

and paid while sharply reducing the hours actually used in production. As a result, the usual tight link between hours worked (the production-relevant margin) and hours paid (the income-relevant margin) broke down. A model without this feature would have to rationalize the collapse in measured output through an implausibly large fall in employment or in total factor productivity.

We capture this with a transitory labor-market shock that drives a wedge between effective hours entering production and the hours underlying labor income. It is modelled as a frictionless labor-demand disturbance: it alters the labor intensity of production at the intensive margin without triggering the hiring or firing costs that govern the extensive margin, consistent with the institutional design of STW schemes. In particular, during the pandemic regime, effective labor input in production differs from paid hours. Effective labor is $L_t\, e^{\epsilon_{L,Covid,t}}$, where $\epsilon_{L,Covid,t}$ is the transitory labor-hoarding shock: a negative realization reduces the hours actually used in production while leaving paid hours unchanged. Value added is accordingly

$$VA_t = \left[\rho_K^{\frac{1}{\theta_{VA}}} \left(u_t^K K_t\right)^{\frac{\theta_{VA}-1}{\theta_{VA}}} + (1-\rho_K)^{\frac{1}{\theta_{VA}}} \left(L_t\, e^{\epsilon_{L,Covid,t}}\right)^{\frac{\theta_{VA}-1}{\theta_{VA}}} \right]^{\frac{\theta_{VA}}{\theta_{VA}-1}} . \tag{A.2}$$

Because the shock affects only the intensive margin, it stabilizes labor income relative to production: paid hours fall by less than effective hours, reproducing the income-stabilization role of STW. This is the channel through which the scheme cushioned household disposable income during 2020–21.

A.3 Regime-Switching Variance and Heteroskedastic Filtering

Adding the two structural shocks is not sufficient on its own. The pandemic quarters are large outliers, and a standard Kalman filter (which assumes a constant innovation variance over the sample) would still misread them, inflating the estimated standard deviations of *all* shocks to fit a handful of extreme observations. Following Lenza and Primiceri (2022) and Cardani et al. (2022), we instead let the variance–covariance matrix of a subset of structural innovations be regime-dependent, while keeping the innovations Gaussian. The structural shocks are

$$u_t \sim \mathcal{N}(0, \Sigma_t)\,, \qquad \Sigma_t = \begin{cases} \Sigma^{(1)}, & t < t^*, \\ \Sigma^{(2)}, & t \geq t^*, \end{cases} \tag{A.3}$$

where t^* denotes the onset of the pandemic regime (2020Q1), and $\Sigma^{(1)}$ and $\Sigma^{(2)}$ are the regime-specific variance–covariance matrices. Only the COVID- and war-related shocks are allowed to switch; the variances of the remaining structural shocks are held constant across regimes. Intuitively, $\Sigma^{(2)}$ absorbs the extraordinary 2020–21 volatility into a separate regime, so that the pre-pandemic regime $\Sigma^{(1)}$—which covers the bulk of the sample—continues to discipline the estimates of persistence and volatility for the ordinary business-cycle shocks.

B Calibrated Parameters

This appendix reports and discusses the calibrated parameters summarized in Section 3.2.

Table B.1: Parameters Calibration: Economic Parameters

Parameter	Calibration	Description
β	0.998	Discount factor
ν_L	0.3	Inverse of the Frisch elasticity of labor supply
h_C^{NR}	0.7	Non-Ricardian habit
δ_k	0.025	Capital depreciation
$\delta_{K_{RES}}$	0.025	Capital depreciation in the renewable-energy sector
γ_P	107.7	Adjustment cost on prices
γ_K	19	Adjustment cost on investment
$\gamma_{K_{RES}}$	19	Adjustment cost on renewable-energy investment
γ_W	180	Adjustment cost on wages
σ_{IMP}	0.1	Elasticity of substitution between domestically produced and imported intermediate goods

Table B.2: Parameters Calibration: Energy-Sector Parameters

Parameter	Calibration	Description
θ_{FOS}	0.9	Elasticity of substitution between the coal-oil composite and gas
θ_D	0.6	Elasticity of substitution between conventional and renewable electricity generation
θ_{COAOIL}	0.3	Elasticity of substitution between coal and oil
θ_{RES}	2	Elasticity of substitution among renewable-energy sources
θ_{EL}	2.65	Elasticity of substitution between domestically produced and imported electricity
θ_{NEL}	2.65	Elasticity of substitution among non-electric energy inputs
$\rho_{EL_{CON}}$	0.63	Factor share of conventional electricity generation
ρ_{COA}	0.56	Factor share of coal within the coal-oil composite
ρ_{COAOIL}	0.22	Factor share of the coal-oil composite within fossil electricity generation
$\rho_{EL_{SOL}}$	0.27	Factor share of solar electricity within renewable electricity generation
$\rho_{EL_{WIN}}$	0.20	Factor share of wind electricity within renewable electricity generation
$\rho_{EL_{BIO}}$	0.17	Factor share of biomass electricity within renewable electricity generation
ρ_{EL}	0.8	Factor share of domestically produced electricity

Tables B.1, B.2 and B.3 report the values of the key calibrated parameters.

Concerning the economic parameters as in Table B.1 the discount factor β is set to 0.998, corresponding to an annual real interest rate of about 1the Euro Area (Albonico et al., 2019). The inverse of the Frisch elasticity of labor supply ν_L is set to 0.3, implying an elastic response of hours to real-wage changes at the intensive margin, in line with the macro, as opposed to micro, estimates commonly adopted in the DSGE literature (Annicchiarico et al., 2015). Habit persistence for non-Ricardian households h_C^{NR} is calibrated at 0.7, capturing the strong consumption inertia of liquidity-constrained

Table B.3: Parameters Calibration: Production, Household and Environmental Parameters

Parameter	Calibration	Description
θ_{Y_H}	2.65	Elasticity of substitution among varieties of domestically produced intermediate goods
ρ_{VA}	0.96	Factor share of value added
ρ_K	0.35	Factor share of capital
θ_{C_F}	0.30	Elasticity of substitution between transport fuel, heating gas and electricity in the household energy bundle
μ_Y	1.02	Emissions elasticity of output
μ_{EL}	0.63	Emissions elasticity of electricity generation
μ_{NEL}	1.20	Emissions elasticity of the non-electric energy sector
ϕ_1^Y	0.03	Abatement-cost parameter
ϕ_2^Y	2.60	Abatement-cost curvature parameter
ϑ^{u_Y}	1.50	Scale parameter of the LINEX abatement-adjustment cost
η^{u_Y}	10.00	Asymmetry parameter of the LINEX abatement-adjustment cost
ϕ_e	3.00	CBAM embodied-carbon and coverage parameter
ϵ^{ETS1}	0.35	Elasticity of EU ETS 1 emissions with respect to the carbon price
ϵ^{ETS2}	0.35	Elasticity of EU ETS 2 emissions with respect to the carbon price
ϕ_1^{REU}	0.2	EU ETS 1 emissions parameter for the rest of the EU
ϕ_2^{REU}	0.2	EU ETS 2 emissions parameter for the rest of the EU

agents, consistent with the evidence on habit formation in open-economy models (Albonico et al., 2019).

The depreciation rate of physical capital δ_k and of clean-energy capital $\delta_{K_{RES}}$ is set to 0.025 per quarter, roughly 10% annually, a standard value. Price and quantity adjustment costs are calibrated to reproduce the slow dynamics of the macroeconomic aggregates. The Rotemberg price adjustment cost γ_P is set to 107.7, broadly in line with the large-scale DSGE literature (e.g., Coenen et al., 2018; Gomes et al., 2010; Christoffel et al., 2008). The implied sluggishness of price adjustment is an important feature for capturing the transitional effects of carbon pricing and energy-price shocks. Investment adjustment costs for both standard and RES capital, $\gamma_K = \gamma_{K_{RES}} = 19$, are set to match the volatility and persistence of investment in Italian data, allowing for realistically slow adjustment to policy shocks (Albonico et al., 2019). Wage adjustment costs are set to $\gamma_W = 180$, consistent with the wage rigidities documented for the Italian labor market and used in related calibration exercises (Annicchiarico et al., 2015; Acocella et al., 2020). The elasticity of substitution between imported goods (subject and not subject to the CBAM) and domestic intermediate inputs, σ_{IMP}, is set to 0.1. This low value is meant to capture the limited substitutability among the different types of imported intermediates and between imported and domestically produced inputs. In this way, the calibration prevents the economy from unrealistically reallocating demand away from CBAM-covered imports towards uncovered imports or domestic inputs in response to small relative-price changes.

The elasticities across electricity inputs (as in Table B.2) reflect technological complementarity among fossil sources and higher substitutability among renewables within the nested CES structure for electricity generation. The elasticity between gas and the coal-oil composite, $\theta_{FOS} = 0.9$, the lower substitutability between coal and oil, $\theta_{COAOIL} = 0.3$, and the elasticity between conventional and renewable electricity generation, $\theta_D = 0.6$, follow the energy-sector calibration of Bartocci and Pisani (2013), whose nested CES power block is consistent with electricity-generation data for Italy and other EU countries and reflects the technical limits to fuel switching in the short run. The high elasticity across renewable technologies, $\theta_{RES} = 2$, captures the strong substitutability among solar, wind, biomass and hydro, as in Annicchiarico et al. (2017) and consistent with EU-level IAMs such as WITCH and DICE. The elasticities across varieties of intermediate goods, $\theta_{Y_H} = 2.65$, between domestically produced and imported electricity, $\theta_{EL} = 2.65$, and among non-electric energy inputs, $\theta_{NEL} = 2.65$, are set consistently with the CES benchmark used for the import and energy-input nests.

The factor shares for electricity generation reflect the empirical composition of Italian power supply: $\rho_{EL_{CON}} = 0.63$ is the share of conventional electricity generation, $\rho_{COA} = 0.56$ is the coal share within the coal-oil composite, and $\rho_{COAOIL} = 0.22$ is the share of the coal-oil composite within fossil generation. These values are consistent with the 2019–2024 averages reported by Terna and Eurostat. The renewable shares, $\rho_{EL_{SOL}} = 0.27$, $\rho_{EL_{WIN}} = 0.20$ and $\rho_{EL_{BIO}} = 0.17$, reflect the relative importance of solar, wind and biomass in Italy's RES mix over the past decade, again following Annicchiarico et al. (2017).

Other parameters are related to production, households and the environmental side of the model. See Table B.3. The elasticity of substitution inside the household energy bundle, θ_{C_F}, governs substitution between transport fuel, heating gas and electricity. It is calibrated from the price-elasticity evidence reported in Faiella and Lavecchia (2021). The domestic electricity share, $\rho_{EL} = 0.8$, is calibrated using the ARERA–Terna electricity balance reported in the 2024 ARERA annual report. Finally, the share of value added in total production, $\rho_{VA} = 0.96$, and of capital within value added, $\rho_K = 0.35$, match Italian national-accounting data and the calibration of Acocella et al. (2020).

The emissions elasticities μ_Y, μ_{EL} and μ_{NEL} map sectoral activity into emissions from intermediate-goods production, fossil electricity generation and the non-electric energy sector, respectively. They are calibrated using ISTAT data for 2020, as reported in the Dynare calibration file. The abatement-cost parameters ϕ_1^Y and ϕ_2^Y follow the DICE tradition: ϕ_1^Y is set to the mean abatement-cost coefficient over the first part of the DICE simulation horizon, while $\phi_2^Y = 2.60$ governs the curvature of the abatement-cost function, following Nordhaus (2018) and the updated DICE calibration in Barrage and Nordhaus (2024). The LINEX abatement-adjustment parameters, $\vartheta^{u_Y} = 1.50$ and $\eta^{u_Y} = 10.00$, follow Annicchiarico and Diluiso (2019) and capture the scale and asymmetry of adjustment costs in abatement effort.

The CBAM parameter $\phi_e = 3.00$ is a reduced-form calibration that converts the bilateral carbon-price differential into an effective border charge by combining the average embodied carbon content of CBAM-covered imports with the effective regulatory coverage of the mechanism. The elasticities of EU ETS 1 and ETS 2 emissions with respect to the carbon price, $\epsilon^{ETS1} = \epsilon^{ETS2} = 0.35$, are calibrated on the cross-country evidence reported by D'Arcangelo et al. (2022), according to which a 10% increase in the carbon price lowers emissions by about 3.5%. Finally, the rest-of-EU emissions parameters, $\phi_1^{REU} = 0.2$ and $\phi_2^{REU} = 0.2$, are calibrated using World Bank carbon-intensity data, measured as kilograms of CO_2 equivalent per 2021 PPP dollar of GDP.

C Data and Estimation Details

C.1 Observables and transformations

The estimation uses quarterly time series for the following 21 variables: real GDP, private consumption, private investment, government consumption, exports, imports, employment (hours worked), wages, the short-term nominal interest rate, long-term government bond yields (10-year), the GDP deflator, the consumption deflator, Euro Area GDP, EA inflation, the government deficit, gas prices, oil prices, the consumer price index for energy, rest-of-the-world GDP, and greenhouse gas emissions for Italy and the EU27. The sample covers 1999Q1–2024Q4, with data drawn mainly from Eurostat, in particular the European System of National Accounts (ESA 2010). All series are seasonally adjusted and expressed in quarterly growth rates where appropriate. A number of transformations ensure consistency with the model's balanced-growth path and stationarity of all relative prices.

C.2 Shock processes

Table C.1 reports the specification of the exogenous processes. Each structural shock follows a first-order autoregressive process with serially uncorrelated Gaussian innovations. To improve the empirical fit and to allow for possible measurement error in the data, measurement errors are permitted for a subset of the observables.

C.3 Posterior simulation and diagnostics

The likelihood is evaluated with the Kalman filter, with regime-switching innovation variances for the COVID-related disturbances as described in Appendix A; the filter also delivers the smoothed estimates of the latent variables. The posterior distribution is obtained through four parallel Markov chains of 400,000 draws each, using the slice-sampling algorithm of Planas et al. (2015) and Calés et al. (2017). Convergence is assessed through cumulative means and the diagnostics of Brooks and Gelman (1998). In addition, the likelihood shape at the posterior mode and the condition number of the Hessian are inspected to detect possible identification problems, after the pre-estimation identification screening based on Iskrev (2010).

Table C.1: Structural Shocks

Shock	Process	Innovation
Supply		
TFP	$A_t = A\, e^{\epsilon_{a,t}}, \quad \epsilon_{a,t} = \rho_a \epsilon_{a,t-1} + \nu_{a,t}$	$\nu_{a,t}$
Price markup	$\mu_t^p = \mu^p\, e^{\epsilon_{\mu,t}}, \quad \epsilon_{\mu,t} = \rho_\mu \epsilon_{\mu,t-1} + \nu_{\mu,t}$	$\nu_{\mu,t}$
Wage markup	$\mu_t^W = \mu^W\, e^{\epsilon_{wl,t}}, \quad \epsilon_{wl,t} = \rho_{wl} \epsilon_{wl,t-1} + \nu_{wl,t}$	$\nu_{wl,t}$
Labor supply	$\epsilon_{sl,t} = \rho_l \epsilon_{sl,t-1} + \nu_{l,t}$	$\nu_{l,t}$
Emissions	$\epsilon_{sz,t} = \rho_z \epsilon_{sz,t-1} + \nu_{z,t}$	$\nu_{z,t}$
Demand		
Discount factor	$\beta_t = \beta\, e^{\epsilon_{c,t}}, \quad \epsilon_{c,t} = \rho_c \epsilon_{c,t-1} + \nu_{c,t}$	$\nu_{c,t}$
Tobin's Q	$\log \Psi_{0,t} = \rho_\psi \log \Psi_{0,t-1} + \nu_{\psi,t}$	$\nu_{\psi,t}$
Domestic demand	$\epsilon_{sy,t} = \rho_y \epsilon_{sy,t-1} + \nu_{y,t}$	$\nu_{y,t}$
Prices		
Consumer prices	$\epsilon_{spc,t} = \rho_{pc} \epsilon_{spc,t-1} + \nu_{pc,t}$	$\nu_{pc,t}$
Energy price	$\epsilon_{spe,t} = \rho_{pe} \epsilon_{spe,t-1} + \nu_{pe,t}$	$\nu_{pe,t}$
External		
Exports	$\epsilon_{sexp,t} = \rho_{exp} \epsilon_{sexp,t-1} + \nu_{exp,t}$	$\nu_{exp,t}$
Imports	$\epsilon_{simp,t} = \rho_{imp} \epsilon_{simp,t-1} + \nu_{imp,t}$	$\nu_{imp,t}$
Oil price	$\epsilon_{oil,t} = \rho_{oil} \epsilon_{oil,t-1} + \nu_{oil,t}$	$\nu_{oil,t}$
Gas price	$\epsilon_{gas,t} = \rho_{gas} \epsilon_{gas,t-1} + \nu_{gas,t}$	$\nu_{gas,t}$
RoW demand	$\epsilon_{RoW,t} = \rho_{RoW} \epsilon_{RoW,t-1} + \nu_{RoW,t}$	$\nu_{RoW,t}$
EA demand	$\epsilon_{YEA,t} = \rho_{YEA} \epsilon_{YEA,t-1} + \nu_{YEA,t}$	$\nu_{YEA,t}$
EA inflation	$\epsilon_{INFEA,t} = \rho_{INFEA} \epsilon_{INFEA,t-1} + \nu_{INFEA,t}$	$\nu_{INFEA,t}$
Policy and financial		
Interest rate	$\epsilon_{R,t} = \rho_{REA} \epsilon_{R,t-1} + \nu_{REA,t}$	$\nu_{REA,t}$
Public deficit	$\epsilon_{sdr,t} = \rho_{dr} \epsilon_{sdr,t-1} + \nu_{dr,t}$	$\nu_{dr,t}$
Public consumption	$\log G_t = (1-\rho_g) \log G + \rho_g \log G_{t-1} + \nu_{g,t}$	$\nu_{g,t}$
Spread	$spread_t = \rho_{spread}\, spread_{t-1} + \beta_{spread}\, \widetilde{b}_t + \nu_{spread,t}$	$\nu_{spread,t}$
COVID-19 (regime-switching variance)		
Forced savings	transitory	$\nu_{C,Covid}$
Labor hoarding	transitory	$\nu_{L,Covid}$

Notes. Each exogenous process follows a first-order autoregressive process with persistence parameter ρ and Gaussian innovation $\nu \sim \mathcal{N}(0, \sigma^2)$. Where a shock enters a level variable, the table also reports the mapping from the AR(1) component to that variable. $\widetilde{b}_t$ denotes the domestic–EA debt-to-output gap. The two COVID-19 disturbances are transitory and their variances are allowed to shift across the pre-COVID and COVID regimes.

D Prior and Posterior Distributions

This appendix reports the prior and posterior distributions of the estimated parameters and shock processes. In each panel, the grey line denotes the prior density, the black line denotes the posterior density, and the green dashed line marks the posterior mode. The figures are grouped by parameter class to facilitate comparison between the prior beliefs and the information contributed by the data.

The innovation standard deviations are identified. For the productivity, preference, investment-quality, export, import, consumer-price, domestic-demand, euro-area, fiscal-deficit, emissions, and COVID-19 shocks, the posterior is concentrated on a region far narrower than the prior and displaced from it (Figures D.1 to D.3). The persistence parameters are estimated with comparable precision for domestic demand, sovereign spreads, inflation, labor supply, trade, and the oil, gas, and foreign-activity processes (Figures D.4 and D.5).

A second set of parameters is identified but concentrates near the boundary of the prior support. The clearest case is the outer-nest elasticity θ_Y, whose posterior mass accumulates against the upper limit of the plotted range, well above the prior mean (Figure D.6).

A third set is only weakly identified. The posteriors of the domestic and consumer-price inflation persistences and of the wage-markup persistence are close to indistinguishable from their priors (Figure D.4), indicating that the data are nearly uninformative about them. The Ricardian share s_R is a less pronounced instance of the same phenomenon: the posterior shifts only marginally and remains diffuse (Figure D.6), consistent with the relatively wide posterior interval reported in Table 3. The consumption elasticity θ_C presents a bimodal posterior (Figure D.6), a configuration typically associated with a likelihood that is nearly flat along that dimension; the reported mode should accordingly be understood as one of two local optima rather than a sharply determined estimate.

A final observation concerns the appearance of the panels rather than the underlying estimates. For several standard deviations, including the public-consumption, interest-rate, euro-area-spread, euro-area-inflation, oil-price, gas-price, and energy-price innovations, the posterior appears as a near-vertical spike, with the prior compressed against the horizontal axis. This reflects the precision of the estimates rather than any identification failure: the posterior intervals in Table E.1 confirm that these parameters are tightly determined. We note it only to caution against over-interpreting the visual contrast across panels.

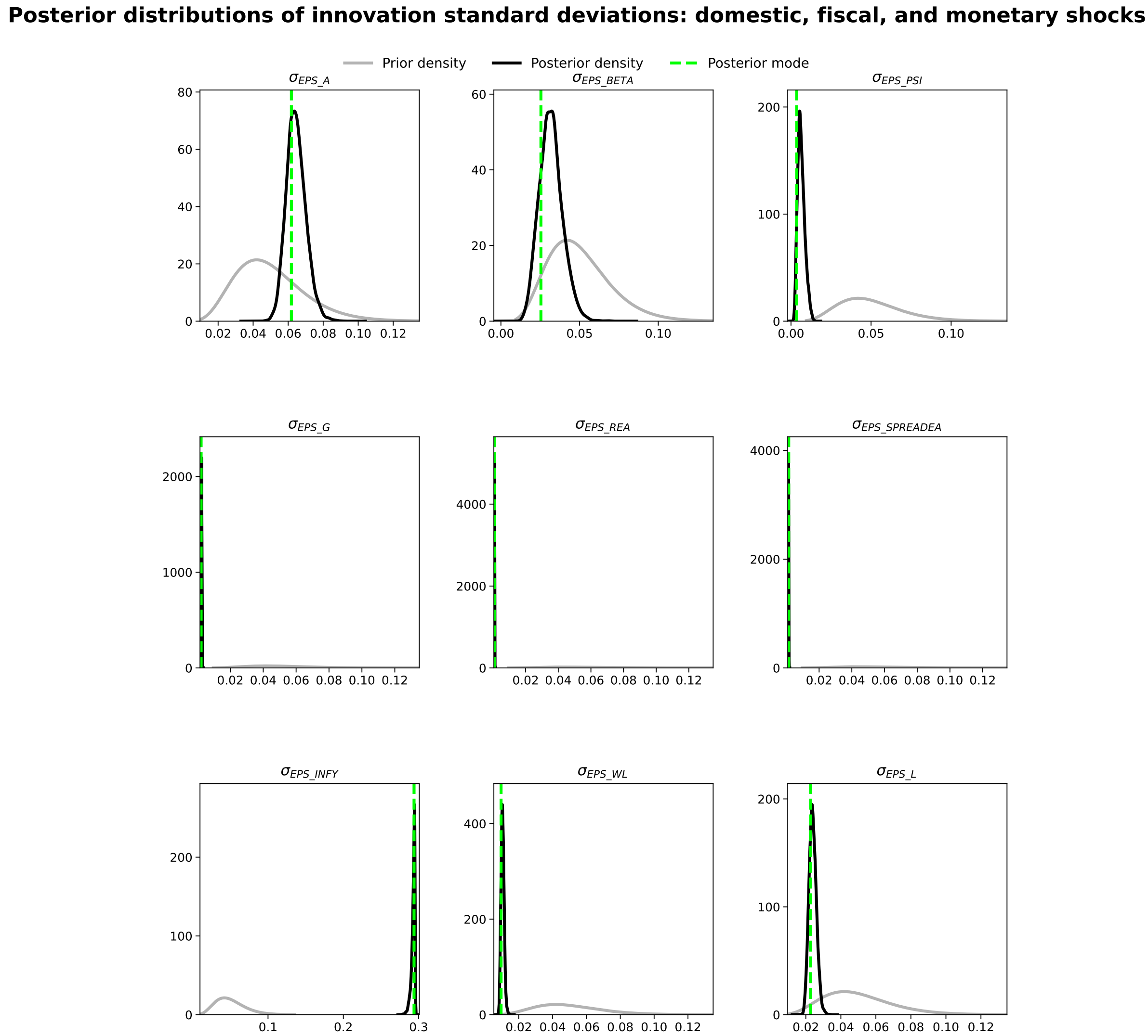

Figure D.1: Prior and posterior distributions of the innovation standard deviations associated with domestic productivity, preference, investment, fiscal, monetary-policy, spread, inflation, wage-markup, and labor-supply shocks.

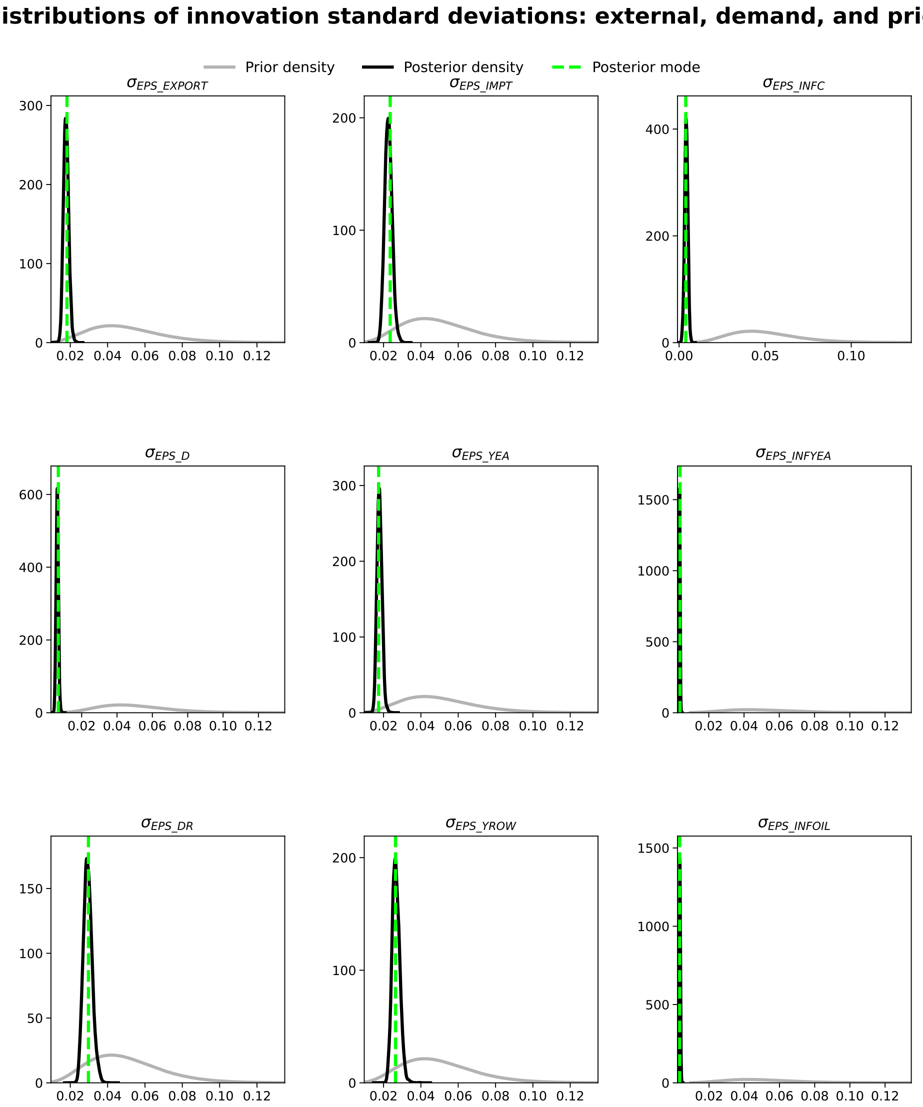

Figure D.2: Prior and posterior distributions of the innovation standard deviations associated with export, import, consumer-price, domestic-demand, euro-area, external, fiscal-deficit, and oil-price shocks.

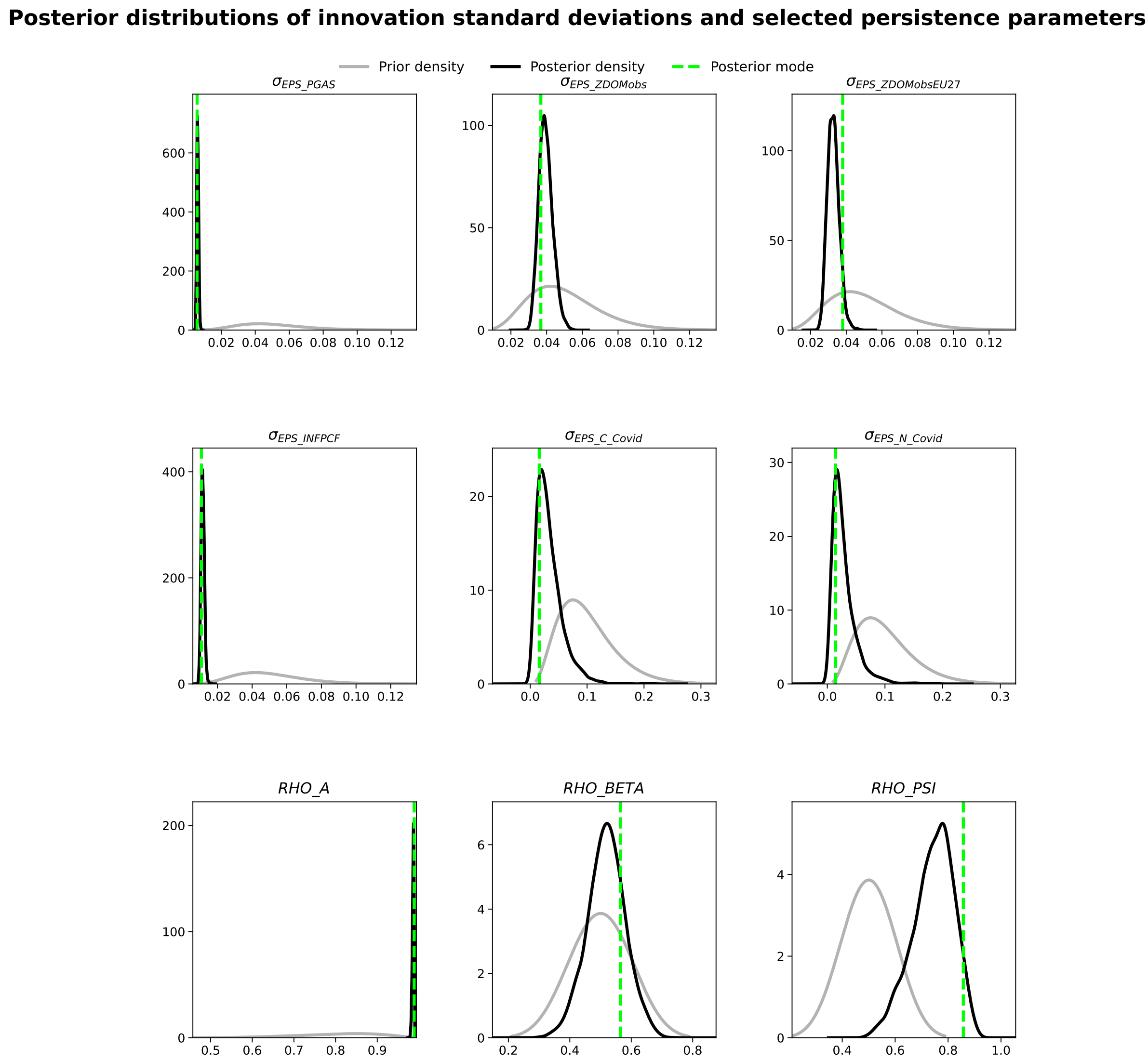

Figure D.3: Prior and posterior distributions of the remaining innovation standard deviations, including gas-price, emissions, energy-price, and COVID-19 shocks, together with the persistence parameters for productivity, discount-factor, and investment-quality disturbances.

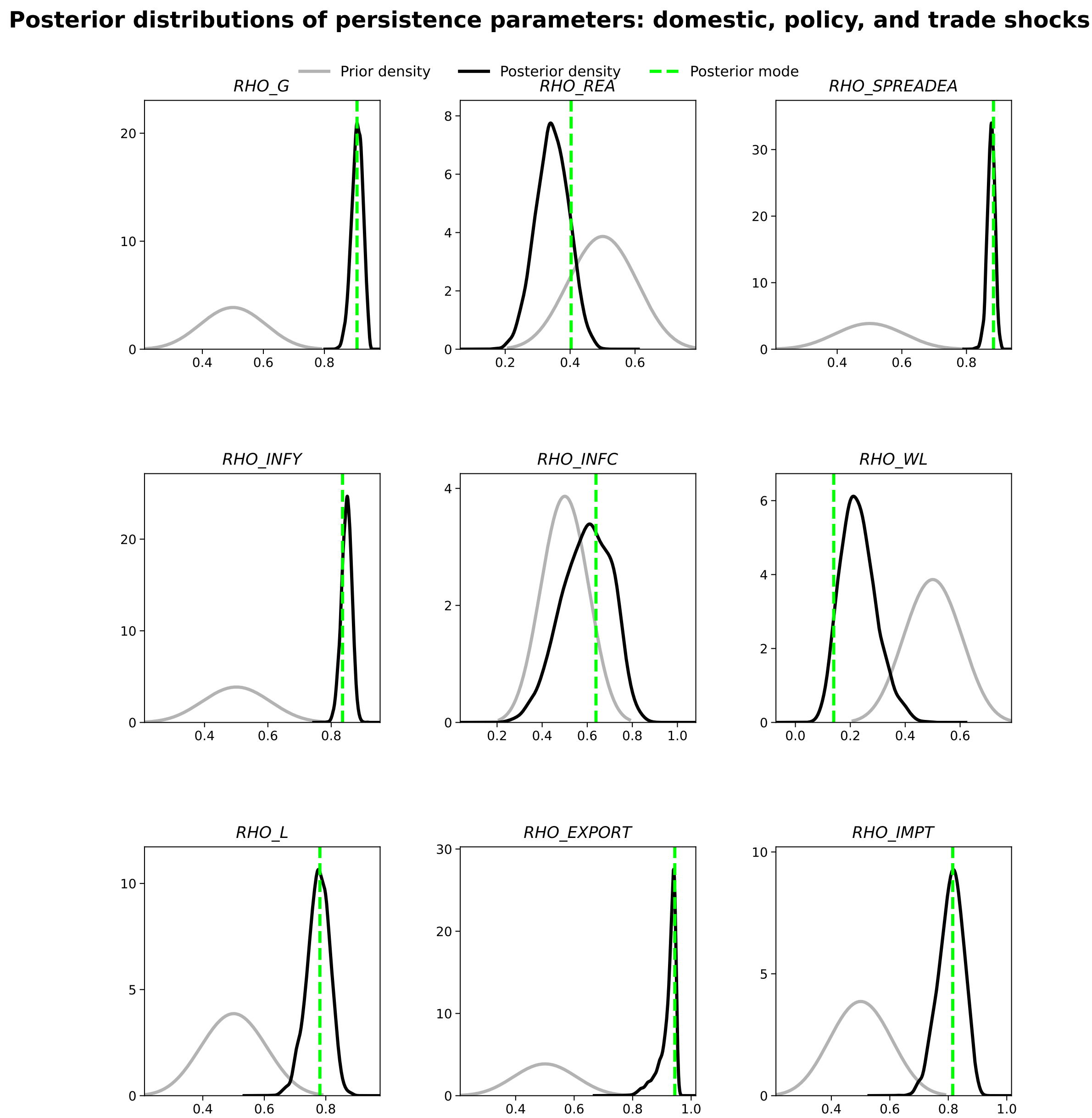

Figure D.4: Prior and posterior distributions of the persistence parameters for domestic demand, monetary policy, sovereign spreads, inflation, wage-markup, labor-supply, export, and import shocks.

Posterior distributions of persistence parameters: external, energy, and emissions shocks

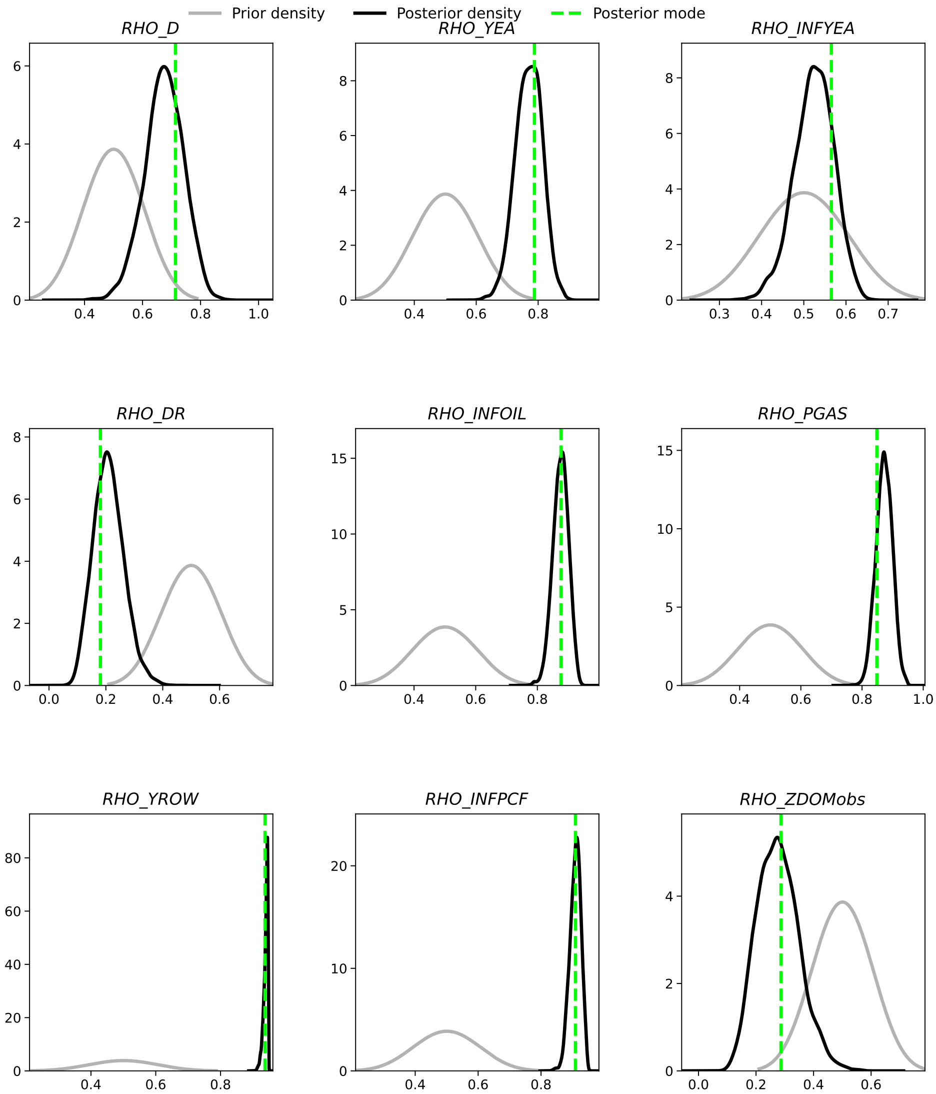

Figure D.5: Prior and posterior distributions of the persistence parameters for demand, euro-area, external, fiscal-deficit, oil-price, gas-price, energy-price, and domestic-emissions shocks.

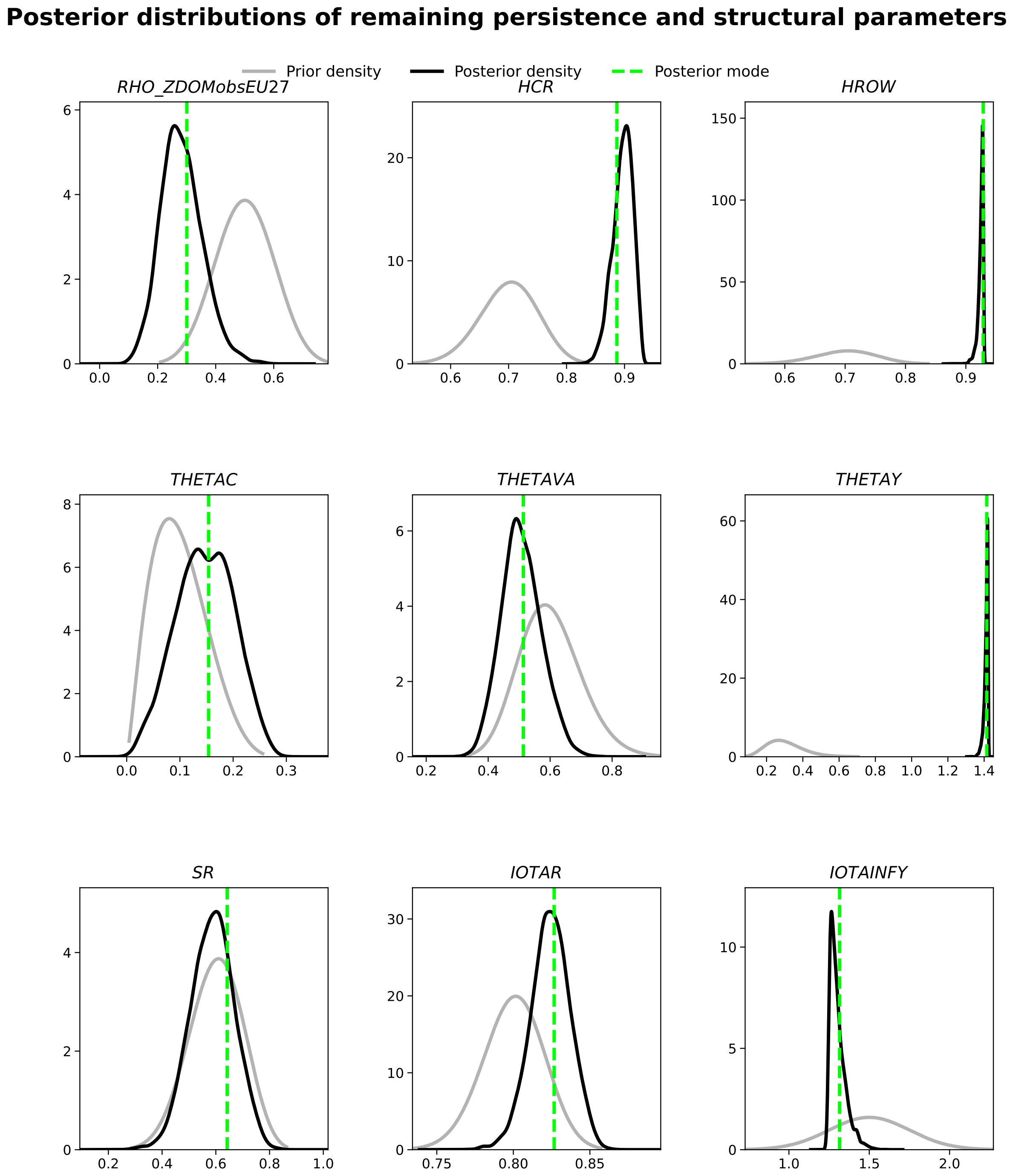

Figure D.6: Prior and posterior distributions of the remaining emissions-persistence parameter and of the estimated structural parameters governing habit formation, substitution elasticities, the Ricardian share, and the monetary-policy rule.

E Estimates of the Persistence and Standard Deviations of the Shocks

This appendix reports the prior means and posterior modes of the persistence parameters and innovation standard deviations of the structural shocks listed in Table C.1. The posterior interval reports the 10th and 90th percentiles of the posterior distribution. For transitory COVID-19 shocks, no persistence parameter is estimated. Innovation standard deviations are reported in the same scale as the estimation output, i.e. in percentage points; the corresponding prior means from the Dynare file are therefore multiplied by 100. The 10th and 90th posterior percentiles for the σ_ν have been rescaled by 100 to match the scale of the posterior mode and the prior–posterior density plot.

Table E.1: Prior and Posterior Estimates of the Structural Shock Processes

Shock	Process	ρ: prior	ρ: mode	ρ: 10–90%	σ_v: prior	σ_v: mode	σ_v: 10–90%
Supply							
TFP	$A_t = Ae^{\epsilon_{a,t}}$	0.800	0.989	[0.983, 0.990]	5.000	6.184	[5.573, 7.350]
Price markup	$\mu_t^p = \mu^p e^{\epsilon_{\mu,t}}$	0.500	0.836	[0.823, 0.875]	5.000	0.294	[0.289, 0.295]
Wage markup	$\mu_t^W = \mu^W e^{\epsilon_{wl,t}}$	0.500	0.140	[0.127, 0.335]	5.000	0.953	[0.883, 1.173]
labor supply	$\epsilon_{sl,t}$	0.500	0.781	[0.714, 0.835]	5.000	2.270	[2.036, 2.716]
Emissions	$\epsilon_{sz,t}$	0.500	0.287	[0.156, 0.386]	5.000	3.676	[3.320, 4.579]
Demand							
Discount factor	$\beta_t = \beta e^{\epsilon_{c,t}}$	0.500	0.565	[0.416, 0.623]	5.000	2.542	[1.893, 4.242]
Tobin's Q	$\log \Psi_{0,t}$	0.500	0.858	[0.626, 0.878]	5.000	0.354	[0.299, 0.980]
Domestic demand	$\epsilon_{sy,t}$	0.500	0.713	[0.561, 0.779]	5.000	0.679	[0.516, 0.727]
Prices							
Consumer prices	$\epsilon_{spc,t}$	0.500	0.639	[0.427, 0.770]	5.000	0.389	[0.258, 0.566]
Energy prices	$\epsilon_{spe,t}$	0.500	0.909	[0.882, 0.939]	5.000	1.067	[0.993, 1.293]
External							
Exports	$\epsilon_{sexp,t}$	0.500	0.944	[0.879, 0.947]	5.000	1.823	[1.558, 2.009]
Imports	$\epsilon_{simp,t}$	0.500	0.815	[0.738, 0.876]	5.000	2.355	[1.917, 2.553]
Oil price	$\epsilon_{oil,t}$	0.500	0.849	[0.827, 0.913]	5.000	0.330	[0.296, 0.389]
Gas price	$\epsilon_{gas,t}$	0.500	0.937	[0.930, 0.947]	5.000	0.577	[0.522, 0.693]
RoW demand	$\epsilon_{RoW,t}$	0.500	0.877	[0.833, 0.914]	5.000	2.643	[2.345, 2.987]
EA demand	$\epsilon_{YEA,t}$	0.500	0.788	[0.706, 0.844]	5.000	1.735	[1.564, 1.990]
EA inflation	$\epsilon_{INFEA,t}$	0.500	0.565	[0.454, 0.603]	5.000	0.368	[0.311, 0.392]

Continued on next page

Shock	Process	ρ: prior	ρ: mode	ρ: 10–90%	σ_v: prior	σ_v: mode	σ_v: 10–90%
Policy and financial							
Interest rate	$\epsilon_{R,t}$	0.500	0.403	[0.262, 0.427]	5.000	0.098	[0.086, 0.113]
Public deficit	$\epsilon_{sdr,t}$	0.500	0.181	[0.127, 0.299]	5.000	2.971	[2.536, 3.287]
Public consumption	$\log G_t$	0.500	0.907	[0.877, 0.936]	5.000	0.224	[0.220, 0.283]
Sovereign spread	$spread_t$	0.500	0.884	[0.858, 0.895]	5.000	0.143	[0.118, 0.153]
COVID-19							
Forced savings	transitory	–	–	–	10.000	1.594	[0.419, 6.420]
Labor hoarding	transitory	–	–	–	10.000	1.450	[0.310, 5.444]

F Decomposing the ETS Package: ETS 1 versus ETS 2

Table F.1: The macroeconomic impact of ETS implementation at year 15: ETS 1 and ETS 2

Variable	ETS 1	ETS 2
GDP – Y	-1.156	-0.015
Consumption – C	-1.279	-0.027
Consumption – Final Good C_Y	-1.275	-0.021
Consumption – Energy C_F	-1.265	-0.230
Consumption – Transport $ROIL$	-1.299	-2.150
Consumption – Electricity EL_C	-1.347	0.196
Consumption – Gas GAS_C	-1.342	-2.156
Hours – L	-0.757	-0.016
Welfare – W	-0.279	-0.005
Wages – w	-1.579	0.001
Labour Productivity – Y/L	-0.398	0.001
Investment – I	-0.935	-0.012
Investment Renewables – $IRES$	-3.083	-0.008
Price – CPI	0.369	0.046
Price markup – Intermediate-good sector μ^p	1.941	0.001
Electricity Price – P_{EL}	0.614	-0.005
Electricity – EL	-2.945	-0.006
Electricity Fossil – $ELFOS$	-3.342	-0.006
Electricity Renewables – $ELRES$	-2.248	-0.005
Electricity Imported – %Y – $ELFY$	-0.013	0.000
Trade Balance – %Y – TBY	-0.224	0.001
Abatement Costs – %Y – CA_Y	0.202	0.000
Revenues ETS – %Y – REV_Y^{ETS}	0.728	0.027
ETS Price €/tCO_2 – P_Z	178.59	166.00

Notes: Values are expressed as percentage deviations relative to the steady state at the time in which the policy is fully implemented, after 15 years, except for variables reported in percent of GDP and carbon prices. The ETS 1 column reports the effects of tightening the producer and power-sector emissions cap, while the ETS 2 column reports the effects of tightening the household fuel and heating emissions cap.