Road to Net Zero: Carbon Policy and Redistributional Dynamics in the Green Transition

(working title)

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Abstract

This paper explores the macroeconomic and distributional impacts of the European Union's transition to net zero emissions, with a focus on carbon pricing and compensation policies. Using an Environmental Dynamic Stochastic General Equilibrium (E-DSGE) model featuring energy and non-energy sectors, as well as heterogeneous households, this study examines the effects of both a short-term shock and a long-term transition. In the short term, a carbon tax shock leads to inflationary pressures and a contraction in output. Over the long term, a gradually increasing carbon tax drives the economy toward zero emissions, with rational agents anticipating income reductions and generating deflationary effects during the transition. Redistribution mechanisms, in the form of direct household transfers and firm subsidies funded by carbon tax revenues, are evaluated for their ability to mitigate inequality and sustain consumption. While direct transfers effectively reduce consumption gaps temporarily, firm subsidies offer broader macroeconomic stabilization. The analysis extends to scenarios with expectation errors, revealing how deviations from anticipated policy paths intensify volatility and alter the trajectory of energy transition dynamics. This research demonstrates the versatility of E-DSGE models in assessing the interplay between carbon policy, inequality, and long-term economic adjustment, offering valuable insights for designing equitable and efficient climate strategies.

JEL Codes: E32, H23, Q43, Q54, Q58

Keywords: Net zero, green transition, inequality, macroeconomic effects, fiscal redistribution, TANK, DSGE.

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1 Introduction

The European Commission (EC) has planned a series of actions, which goes by the name of European Green Deal, to reduce national greenhouse gas (GHG) emissions to "Net Zero" by 2050 in the European Union (EU), in accordance with the terms of the United Nations Conference of the Parties (COP). The term Net zero refers to a state in which the anthropogenic GHG emissions going into the atmosphere are balanced by removal out of the atmosphere, either via natural sinks (land or oceans) or technical removal (air or biomass capture and geological storage). This corresponds to an average reduction of emissions between 95% and 97% from the 1990 level.

Economically disincentivizing greenhouse gas emissions is widely considered the most effective reduction strategy. This measure can be implemented through price-based instruments such as carbon taxes or emission allowances(like the cap-and-trade system currently in use in the EU). Results from the empirical literature on the macroeconomic impact of these measures in the EU are quite controversial. Metcalf and Stock (2023) analyze the impact of national carbon taxes across European countries, finding negligible, if not positive in some cases, effect on GDP and employment. On the contrary, Känzig and Konradt (2023) find that EU wide emission trading scheme (ETS) can have negative implications for the economy. Additionally, some studies show that costs are not equally distributed, and that the danger of negative distributional effects is real either across countries (Berthold et al. 2023) and within the society (Eurofound 2021; Känzig 2023; Zachmann et al. 2018).These distributional effects can be summarized into three main categories:

1. a price effect, as it raises goods prices given the additional cost firms have to face;
2. an income effect, as it alters the return to factors of production (capital and labor);
3. a wealth effect, as it affects the asset values.

Consumption baskets differ significantly across income levels, with goods from carbon-intensive sectors—such as energy, fuel, and agriculture—constituting a larger share of spending for low-income households. These households often lack savings and access to capital markets, which limits their ability to smooth consumption over time and increases their exposure to economic shocks. EU-level data reveal that the top two income quintiles hold 60–70% of total wealth, underscoring the disparity between low- and high-income households.

Consequently, low-income households are more likely to bear a disproportionate share of the welfare costs associated with current carbon tax policies. European institutions acknowledge that achieving a socially fair transition is essential for making the transition politically feasible (European Commission 2018). To address this, the EC has designed several compensation mechanisms[1] aimed at supporting the most vulnerable and exposed households, including programs such as the *Social Climate Fund* (SCF) and the *Just Transition Fund* (JTF).

Building on empirical evidence and current European policy, this paper aims to provide a theoretical analysis of the macroeconomic and distributional effects of the EU's transition to an economy with net zero emissions. The focus is on the effectiveness of compensation policies aimed at reducing inequality. Both short- and long-term dynamics are studied using an Environmental-DSGE model. The model includes energy and non-energy sectors, along with heterogeneous households. In the short-term analysis, the economy experiences a persistent carbon tax shock, while in the long-term, the transition to a zero-emission economy is driven by a gradually increasing carbon tax. The analysis considers four redistribution policies: two direct transfer schemes to households to support consumption and two labor subsidy schemes to firms, all funded through carbon tax revenues. The findings indicate that while a temporary carbon tax shock leads to inflationary pressures and a short-term reduction in output, long-term simulations under perfect foresight reveal that the policy becomes soon deflationary as agents anticipate future income reductions. Along the transition, driven by the exogenously increasing carbon tax, dirty energy and non-energy firms are incentivized to fully abate their emissions[2]. By increasing production costs for the polluting sectors along the transition, resources are permanently reallocated towards green energy producers, which become relatively bigger in the new steady state at the expense of polluting firms. Rational agents, fully aware of the carbon tax trajectory, anticipate the fall in income and adjust their behavior accordingly. This leads to a contraction in production as the demand effect prevails. This dynamic introduces deflationary pressures as the economy adjusts[3].

[1] An example of how the carbon tax revenues are employed to offset the adverse effects of the green transition outside EU, is the revenue-neutral carbon tax in British Columbia (Canada): here it is found that tax redistribution could stimulate demand for products and hence workers (Yamazaki 2017).

[2] The model currently assumes that the transition is achieved solely and exclusively through carbon taxation. The inclusion of complementary measures that facilitate the green transition (by decreasing abatement costs and/or reducing the energy dependence and emission intensity of the non-energy sector over time) will be examined in an updated version of the paper.

[3] Similarly, Ferrari and Nispi Landi (2024b) use a simple AD-AS model to show how a gradual increase

Distributional effects – price and income effects – are detected along the transition. Unless carbon tax revenues are redistributed, all households experience huge welfare losses, and the poorest households see their consumption decline the most in relative terms. Redistribution of carbon tax revenues through direct household transfers or firm subsidies can mitigate income inequality, with direct transfers proving most effective in reducing the consumption gap, though only temporarily. These findings highlight the importance of implementing effective redistribution mechanisms to ensure a just transition to a green economy. A full comparison of all possible scenarios is provided in the paper.

Literature Review

The synthesis in the literature between climate dynamics and economic models has evolved along two main pathways. The first finds expression in the integrated assessment models (IAMs). Nordhaus's dynamic integrated model of climate and the economy (DICE) (Nordhaus 1977, 2010; Nordhaus and Sztorc 2013) is a pioneering example, weaving climate dynamics into the global macroeconomic system. This approach has been expanded to address inequality issues associated with environmental policies and the green transition, as described in the studies by Dennig et al. (2015), Emmerling and Tavoni (2021), and Zhao et al. (2022). These kinds of models have a general equilibrium structure at their core, and are frequently used for studying long-term climate policy impacts, especially on a global scale. However, they often tend to oversimplify the economy's microfoundations and household heterogeneity. The second path focuses on the impact of climate change and environmental policies on the short-term business cycle through E-DSGE. Initial models, such as those by Fischer and Springborn (2011) and Heutel (2012), have been expanded to include Neo-Keynesian (NK) nominal rigidities (Annicchiarico and Di Dio 2015, 2017), financial frictions (Carattini et al. 2023), and labor market frictions (Gibson and Heutel 2023). This paper builds on these extensions by incorporating both energy and non-energy sectors into the E-DSGE framework, within a context of nominal rigidities and other frictions. More recently, Känzig (2023) and Benmir and Roman (2022) have explored the impact of carbon pricing on emissions, economic aggregates, and inequality (in the EU and the US respectively), focusing

in emissions taxation, in a context where agents anticipate future tax rises, leads to a reduction in demand, putting downward pressure on prices. The demand effect becomes dominant and the transition policy deflationary.

on short-term implications. Benmir and Roman (2022) also extends to scenarios involving sticky prices, inflationary pressures and abatement learning. Finally, this paper draws on the literature on two-agent (TA) models, in the spirit of Bilbiie (2008), which introduces a distinction between credit-constrained households and savers in dynamic general equilibrium models. The choice of a TANK-EDSGE[4] model is due to the fact that the microfoundations underlying DSGE models allow for a more detailed examination of distributional dynamics, including how income groups are affected differently by taxation and redistribution mechanisms, in a general equilibrium framework. In addition, the DSGE framework allows for the study of different expectation formations, including both standard perfect foresight and expectation error scenarios. This allows for a detailed examination of how agents' forecast inaccuracies affect the transition and distributional dynamics under carbon pricing.

A closely related study is Coenen et al. (2024). Their work focuses on medium-term effects, leveraging constrained and unconstrained households and simulating various redistribution schemes and green subsidies. While similar in its use of carbon taxation as a policy lever, this paper departs from Coenen et al. (2024) in several ways. First, it extends the analysis to long-term scenarios, until the 2050 Net Zero target, capturing the enduring dynamics of carbon taxation. Second, it introduces richer heterogeneity among households, incorporating differences in energy consumption shares and elasticities of substitution. Third, it considers the effects of applying a carbon tax to both energy and non-energy sectors, highlighting interactions often overlooked in models focused solely on energy emissions. Finally, this paper systematically compares redistribution schemes in both the short and long run, offering new insights into their relative effectiveness in mitigating consumption and income inequality.

In summary, my paper extends this second strand of literature by offering a comprehensive analysis of both short- and long-run macroeconomic and distributional effects. Combining the short-term insights on distributional impacts of Känzig (2023) with the long-term perspectives on transition effects of Ferrari and Nispi Landi (2023)[5] into a single framework provides interesting new insights into the dynamics of carbon pricing and redistribution mechanisms. This broadens the scope of traditional DSGE models, offering a significant methodological

[4]In full, it reads Two Agents New Keynesian Environmental Dynamic Stochastic General Equilibrium.

[5]The authors provide valuable insights into the long-term effects of central banks' Green QE policies during the transition to a carbon-free economy in the EU, though their focus is mainly macroeconomic rather than distributional.

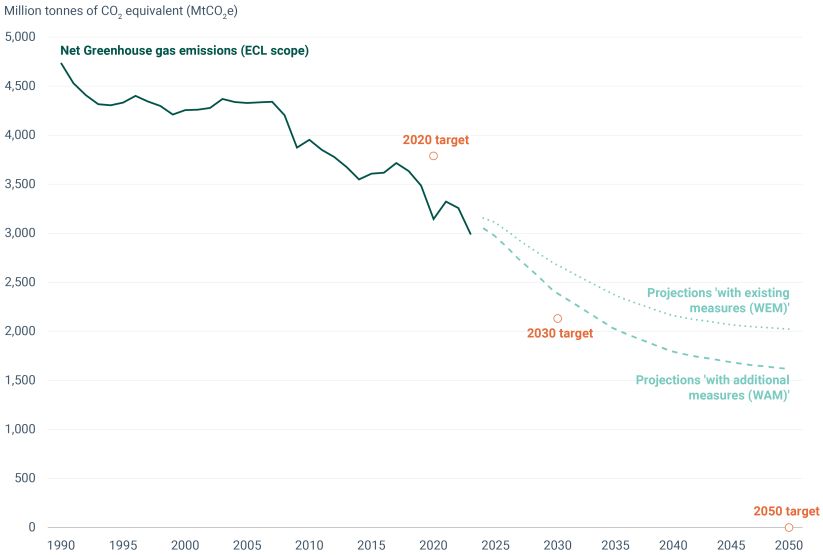
contribution to the analysis of carbon pricing and inequality issues associated with the net zero policy.

The remainder of the paper is structured as follows. Section 2 describes the current situation in the EU regarding environmental policies and the goal of reducing emissions by 2050. Section 3 presents the model equations and the various redistribution policies. In Section 4.1, I simulate the effects of stochastic carbon tax shocks in the E-DSGE framework. Section 4.2 explores long-term dynamics using a perfect foresight approach, with an extension to analyze expectation errors. Finally, Section 5 concludes.

2 Emissions and Environmental Policy Framework in the EU

To get an idea of the current situation of GHG emissions in the EU, let's look at the graph 1. Total emissions projections for the EU-27 show a general downward trend over the past decades. Despite this positive trajectory, the current projections, as reported by the European Environment Agency, fall short of the reductions needed to meet the mid-term climate goals set for 2030. They are also not aligned with the more ambitious long-term goal of achieving net zero emissions by 2050. The gap between projected emissions and targets highlights a significant challenge: existing environmental policies are still not sufficient to deliver the required level of emissions reductions. This underscores the urgent need for stronger climate actions to close this gap and ensure that the EU can meet its climate goals in both the short- and long-term.

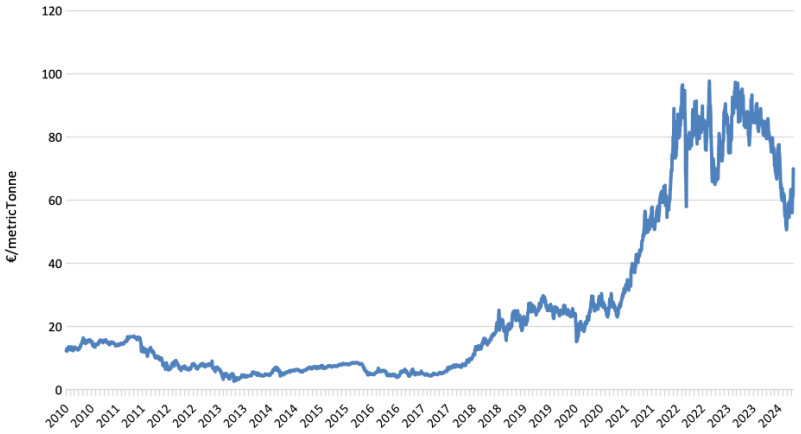
Figure 1: Total emissions projections, EU-27



Source: Member States' greenhouse gas (GHG) emission projections, 2024, European Environment Agency (EEA); National emissions reported to the UNFCCC and to the EU Greenhouse Gas Monitoring Mechanism, April 2024; Approximated estimates for greenhouse gas emissions, 2023

The main instrument for reducing polluting emissions cost-effectively is that of emission allowances, traded within the EU Emission Trading System (EU-ETS), a carbon trading scheme introduced in 2005. The EU-ETS it covers 45% ca. of EU GHG emissions[6]. Companies trade emission rights on the carbon market or through the EU-ETS auctions (European Energy Exchange- EEX). The up-to-date path of ETS spot prices is shown in figure 2.

Figure 2: ETS Spot Price, €/metric Tonne, 2010-2025



Source: Datastream. Available: LSEG Workspace.

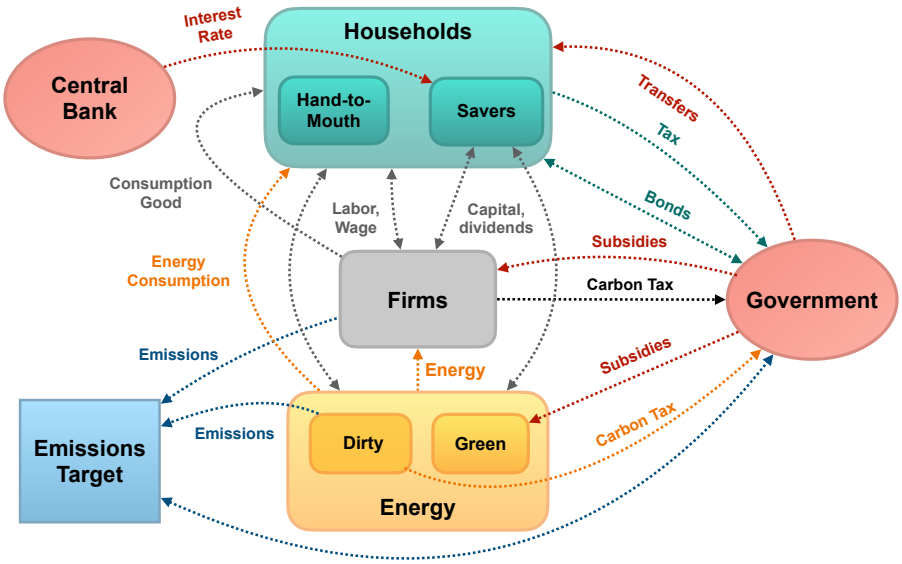
[6]By 2027, the European Commission will introduce the EU-ETS2, a new emissions trading system that will complement the existing one. This system will cover emissions from buildings, road transport, and additional sectors, and is expected to replace the national carbon taxes currently implemented in many EU countries.

To complement its goal of achieving net zero emissions by 2050, the EC has set several additional objectives under the European Green Deal. One of the key goals is to ensure that the transition is "just," ensuring that "no person and no place is left behind." For example, the SCF provides funding to EU Member States to support vulnerable groups affected by the green transition, such as those in energy or transport poverty, ensuring they are not left behind. Member States can use the SCF for structural measures and investments in energy efficiency and renewable energy integration. It can also allocate resources for temporary direct income support. The JTF also supports the green transition by facilitating employment opportunities in emerging sectors, promoting low-carbon technologies, and encouraging economic diversification through climate-resilient investments and jobs.

3 Model

The design of the model builds upon the foundations laid by existing literature on environmental macroeconomics (Annicchiarico and Di Dio 2015, 2017; Ferrari and Nispi Landi 2024a; Hassler et al. 2021, 2022; Heutel 2012) and two-agents DSGE models (Bilbiie 2008; Galí et al. 2007). However, this paper extends and adapts these frameworks to incorporate additional features tailored to the analysis of the EU's Net Zero transition, such as a disaggregated energy sector, energy use for consumption good production, heterogeneous energy consumption, dual-sector taxation, and long-term dynamics. A sketch of the model is shown in figure 3.

Figure 3: Scheme of the Two-Agents E-DSGE model.



3.1 Households

There is a continuum of infinitely lived households $[0, 1]$ with the same utility function $U(\cdot)$. Households gain utility from consumption x and disutility from labor l. As in Bilbiie (2008), a fixed share of families $(1 - \Delta)$ has access to capital and bond markets, owns final-good firms and supplies labor, maximizing the standard intertemporal problem $\max \mathbb{E}_t \sum_{i=0}^{\infty} \beta^i U\left(x_{S,t+i}, l_{S,t+i}\right)$, where β is the intertemporal discount factor[7]. I call this group savers (S). The rest of the households Δ has no assets and consume the entire budget each period. I call these households hand-to-mouth (HM). The utility function takes the additively separable CRRA form as follows:

$$U\left(x_{j,t}, l_{j,t}\right) = \frac{x_{j,t}^{1-\varphi_c} - 1}{1 - \varphi_c} - \psi_j \frac{l_{j,t}^{1+\varphi_l}}{1 + \varphi_l}, \text{ where j=\{HM,S\}} \tag{1}$$

φ_c is the inverse elasticity of intertemporal substitution; ψ_j weights the disutility of working and φ_l is the inverse of the Frisch elasticity.

[7]The expectation operator is ignored in the notation that follows, since in a perfect foresight model the economic actors know exactly how macroeconomic variables will develop into the future, effectively zeroing out the expectations component. The same is not true in the case of a stochastic simulation; but for simplicity in what follows I will show only the notation related to the perfect foresight model.

3.1.1 Hand-to-mouth

Hand-to-mouth households maximize their utility with respect to consumption and labor, subject to their budget balance:

$$p_{HM,t}x_{HM,t} = w_t l_{HM,t} + \mathcal{T}_t^{HM} \tag{2}$$

where $p_{HM,t}$ is the HM price index, w_t is wage and $\mathcal{T}_{HM,t}$ represents fiscal transfers from the government. From the first order conditions (FOCs), I get HM labor supply

$$\frac{{x_{HM,t}}^{-\varphi_c}}{p_{HM,t}} w_t = \psi_{HM} {l_{HM,t}}^{\varphi_l} \tag{3}$$

3.1.2 Savers

Savers' budget reads:

$$b_t + p_{S,t}x_{S,t} + i_t = b_{t-1}\frac{r_{t-1}}{\pi_t} + r_t^k k_{t-1} + w_t l_{S,t} + \mathcal{T}_t^S \tag{4}$$

where b_t represents bond holdings, i_t represents investment, $b_{t-1}r_{t-1}$ denotes revenues from holding bonds, $k_{t-1}r_t^k$ is the income from capital service, $w_t l_{S,t}$ is the income from labor and $\mathcal{T}_{S,t}$ represents fiscal transfers from the government. All variables are expressed in real terms. The law of motion of capital with quadratic adjustment costs is

$$k_t(i) = (1-\delta)k_{t-1}(i) + i_t(i)\left[1 - \frac{\phi_i}{2}\left(\frac{i_t(i)}{i_{t-1}(i)} - 1\right)^2\right], \tag{5}$$

where $\phi_i > 0$ denotes the investment cost parameter. S' intertemporal utility maximization yields the following FOCs with respect to x_t, $l_{S,t}$, k_t and i_t:

$$p_{St}\,\lambda_{St} = {x_{St}}^{(-\varphi_c)} \tag{6}$$

$$w_t\,\lambda_{St} = \psi_S\,{l_{St}}^{\varphi_l} \tag{7}$$

$$q_t = \beta\mathbb{E}_t\,\frac{\lambda_{St+1}}{\lambda_{St}}\,\left(rk_{t+1} + q_{t+1}\,(1-\delta)\right) \tag{8}$$

$$\begin{aligned} 1 =& q_t\left[1 - \frac{\phi_i}{2}\left(\frac{i_t}{i_{t-1}} - 1\right)^2 - \phi_i\left(\frac{i_t}{i_{t-1}} - 1\right)\frac{i_t}{i_{t-1}}\right] \\ &+\beta\mathbb{E}_t q_{t+1}\left[\frac{\lambda_{S,t+1}}{\lambda_{S,t}}\phi_i\left(\frac{i_{t+1}}{i_t} - 1\right)\left(\frac{i_{t+1}}{i_t}\right)^2\right], \end{aligned} \tag{9}$$

where λ_S is the marginal utility of consumption. From the FOC for b_t, I obtain the Euler equation:

$$\lambda_{S,t} = \beta \mathbb{E}_t \left(\lambda_{S,t+1} \frac{r_t}{\pi_{t+1}} \right) \tag{10}$$

3.1.3 Consumption basket

Households consume energy and non-energy goods. The consumption basket x_t takes a constant elasticity of substitution (CES) form as follows:

$$x_{j,t} = \left[\gamma_j^{\frac{1}{\epsilon_j}} c_{j,t}^{\frac{\epsilon_j - 1}{\epsilon_j}} + (1-\gamma_j)^{\frac{1}{\epsilon_j}} E_{j,t}^{c\,\frac{\epsilon_j - 1}{\epsilon_j}} \right]^{\frac{\epsilon_j}{\epsilon_j - 1}} \tag{11}$$

where γ_j i a distribution parameter derived from the share of energy good in the consumption basket and ϵ_j is the elasticity of substitution between energy $E_{j,t}^c$ and non-energy $c_{j,t}$ goods. Both parameters differ across households groups. The price index reads

$$p_{j_t} = \left(1 - \gamma_j + \gamma_j \, p_{E,t}^{1-\epsilon_j} \right)^{\frac{1}{1-\epsilon_j}} \tag{12}$$

I define $p_{j,t} \equiv \frac{P_{j,t}}{P_{y,t}}$, $1 \equiv \frac{P_{y,t}}{P_{y,t}}$ and $p_{E,t} \equiv \frac{P_{E,t}}{P_{y,t}}$ as the price of consumption bundle, non-energy and energy goods in terms of non-energy good price (numeraire). The demand for the two consumption goods is as follows:

$$c_{j,t} = \gamma_j \left(\frac{1}{p_{j,t}} \right)^{-\epsilon} x_{j,t} \tag{13}$$

$$E_{c,j,t} = (1-\gamma_j) \left(\frac{p_{E,t}}{p_{j,t}} \right)^{-\epsilon} x_{j,t} \tag{14}$$

3.2 Firms

From the production side, the model features two perfectly competitive sectors, producing consumption goods and energy, respectively. The non-energy firms employ energy and value added (bundle of labor and capital) as input. Polluting emissions are a byproduct of industrial production. The energy sector consists of two kind of firms, "green" and "dirty", characterized by sector specific technology, labor and capital. The energy output is a composite of these two energy sources, which are intended to be good substitutes. Only dirty energy firms produce GHG emissions. Technologies adopted in all sectors do not grow over time, but are fixed at

the steady-state level. This assumption allows us to isolate the potential of carbon tax alone in reducing emissions and its effect on the economy.

3.2.1 Non-energy good producers

Each firm (i) produces a non-energy consumption good $y_t(i)$ according to the following CES function:

$$y_t(i) = \left[\upsilon^{\frac{1}{\xi_y}} \left(VA_t(i) \right)^{\frac{\xi_y - 1}{\xi_y}} + (1-\upsilon)^{\frac{1}{\xi_y}} \left(A_{E,t} E_{y,t}(i) \right)^{\frac{\xi_y - 1}{\xi_y}} \right]^{\frac{\xi_y}{\xi_y - 1}}, \tag{15}$$

$$\text{where } VA_t(i) = A_{y,t}(i) \left(k_{y,t-1}(i) \right)^{\alpha} \left(l_{y,t}(i) \right)^{1-\alpha} \quad \text{with} \quad \alpha \leq 1 \tag{16}$$

$$\text{and} \quad A_{y,t}(i) = (1 - D_t(e_{s,t})) \tag{17}$$

$A_{E,t}$ is energy technology and $A_{y,t}$ is the value added technology and TFP_t is the total factor productivity net of the damage function D_t; $k_{y,t-1}$ and $l_{y,t}$ are sector specific capital and labor and $E_{y,t}$ is the energy input. α represents capital input share in the value added. $1 - \upsilon$ defines the share of energy in the production function, and ξ_y is the elasticity of substitution between value added and energy component. Polluting emissions are a function of firms' production and abatement

$$e_{y,t}(i) = y_t(i) \gamma_y \left(1 - \mu_{y,t}(i) \right) \tag{18}$$

where $\mu_{y,t}$ is the fraction of sectoral emissions abated. The abatement function is defined as follows:

$$g\left(\mu_{y,t}(i) \right) = \theta_1 (\mu_{y,t}(i))^{\theta_2} \tag{19}$$

Firms' profit function is expressed in terms of the non-energy good price as follows:

$$\begin{aligned} \Pi_{y,t}(i) &= y_t(i) - \left(w_t - \mathcal{T}_{y,t} \right) l_{y,t}(i) - r_{k,t} k_{y,t-1}(i) - \tau_{y,t}(i) e_{y,t}(i) \\ &- g\left(\mu_{y,t}(i) \right) y_t(i) - p_{E,t} E_{y,t}(i) \end{aligned} \tag{20}$$

where $\tau_{y,t}$ is the sectoral emissions tax and $\mathcal{T}_{yt}$ is a labor cost subsidy. Given all firms are equal, I can drop the index (i). From firm's profit maximization problem, the FOC with

respect to $k_{y,t}$ yields the demand for capital:

$$rk_t = VA_t^{\frac{\xi_y - 1}{\xi_y}} \upsilon^{\frac{1}{\xi_y}} \alpha \frac{mc_{y,t}}{k_{y,t}} y_t^{\frac{1}{\xi_y}}, \tag{21}$$

where $mc_{y,t}$ is the Lagrangian multiplier related to marginal costs. From the FOC with respect to $l_{y,t}$, I obtain the sectoral labor demand:

$$w_t - \mathcal{T}_{y,t} = VA_t^{\frac{\xi_y - 1}{\xi_y}} \upsilon^{\frac{1}{\xi_y}} y_t^{\frac{1}{\xi_y}} (1 - \alpha) \frac{mc_{y,t}}{l_{y,t}}, \tag{22}$$

FOC with respect to $E_{y,t}$ yields the energy demand for production:

$$p_{E,t} = (1 - \upsilon)^{\frac{1}{\xi_y}} mc_{y,t} y_t^{\frac{1}{\xi_y}} E_{y,t}^{\frac{(-1)}{\xi_y}} \tag{23}$$

From the FOC with respect to $\mu_{y,t}$, I get the opportunity cost of abatement with respect to the emissions tax:

$$\tau_{y,t}\gamma_y = \theta_1\theta_2(\mu_{y,t})^{\theta_2 - 1} \tag{24}$$

Finally, the real marginal cost of non-energy producers reads:

$$mc_{y,t} = 1 - \Big(\theta_1(\mu_{y,t})^{\theta_2} + \tau_{y,t}\gamma_y (1 - \mu_{y,t})\Big) \tag{25}$$

3.2.2 Energy sector

Energy producers aggregate renewable (green) $E_{G,t}$ and non-renewable (dirty) $E_{D,t}$ energy intermediates, according to a CES technology, to produce the energy good E_t used for consumption by households and as a production factor by non-energy producers:

$$E_t = \left[\nu^{\frac{1}{\chi}} (E_{G,t})^{\frac{\chi - 1}{\chi}} + (1 - \nu)^{\frac{1}{\chi}} (E_{D,t})^{\frac{\chi - 1}{\chi}}\right]^{\frac{\chi}{\chi - 1}} \tag{26}$$

where ν represents the share of green energy and χ is the elasticity of substitution between the two intermediate energy inputs. The aggregate energy price is

$$p_{E,t} = \left[\nu\, {p_{G,t}}^{1-\chi} + (1 - \nu)\, p_{D,t}^{1-\chi}\right]^{\frac{1}{1-\chi}} \tag{27}$$

The demand for green and dirty energy intermediates is respectively:

$$E_{G,t} = \nu \left(\frac{p_{G,t}}{p_{E,t}} \right)^{-\chi} E_t, \tag{28}$$

$$E_{D,t} = (1-\nu) \left(\frac{p_{D,t}}{p_{E,t}} \right)^{-\chi} E_t \tag{29}$$

The two intermediate energy producers employ a Cobb-Douglas technology, with sector specific capital and labor supplied by households. The maximization problem of dirty energy producers reads:

$$\max_{l_{D,t}, k_{D,t-1}, \mu_{D,t}} \quad p_{D,t} E_{D,t} - \tau_{D,t} E_{D,t} - \theta_1 \left(\mu_{D,t}\right)^{\theta_2} E_{D,t} - w_t l_{D,t} - r_{k,t} k_{D,t-1} \tag{30}$$

$$s.t. \qquad E_{D,t} = A_{D,t} \left(k_{D,t-1}\right)^{\alpha_E} \left(l_{D,t}\right)^{1-\alpha_E}. \tag{31}$$

Non-renewable energy firms face a trade-off between paying the environmental tax $\tau_{D,t}$ on their polluting emissions $E_{D,t}$ or sacrifice a share of their output to abate emissions. The fraction of emissions from energy production that are abated is $\mu_{D,t}$. GHG emissions are again a function of dirty energy production and abatement

$$e_{D,t}(i) = E_{D,t}(i) \gamma_D \left(1 - \mu_{D,t}(i)\right) \tag{32}$$

where $\mu_{D,t}$ is the fraction of dirty energy emissions abated. The abatement function reads

$$g\left(\mu_{D,t}(i)\right) = \theta_1 (\mu_{D,t}(i))^{\theta_2} \tag{33}$$

From FOC with respect to $k_{D,t}$, $l_{D,t}$ and $\mu_{D,t}$ I obtain:

$$r k_t = \alpha_e \frac{E_{D,t}}{k_{D,t}} \left(p_{D,t} - \tau_{D,t} \gamma_D \left(1 - \mu_{D,t}\right) - \theta_1 \mu_{D,t}^{\theta_2} \right) \tag{34}$$

$$w_t = \left(p_{D,t} - \tau_{D,t} \gamma_D \left(1 - \mu_{D,t}\right) - \theta_1 \mu_{D,t}^{\theta_2} \right) \left(1 - \alpha_e\right) \frac{E_{D,t}}{l_{D,t}} \tag{35}$$

$$\tau_{D,t} \gamma_D = \theta_1 \theta_2 \mu_{D,t}^{\theta_2 - 1} \tag{36}$$

The maximization problem of green energy producers reads:

$$\max_{l_{G,t}, k_{G,t-1}} \quad p_{G,t} E_{G,t} - (w_t - \mathcal{T}_{G,t}) l_{G,t} - r_{k,t} k_{G,t-1} \tag{37}$$

$$s.t. \qquad E_{G,t} = A_{G,t} \left(k_{G,t-1}\right)^{\alpha_E} \left(l_{G,t}\right)^{1-\alpha_E}, \tag{38}$$

where $\mathcal{T}_{G,t}$ is a subsidy to green labor, The function of these public subsidies is to directly reduce the cost of labor for renewable energy producers. The FOC of green energy firms problem are:

$$rk_t = p_{G,t}\, \alpha_e \frac{E_{G,t}}{k_{G,t}} \tag{39}$$

$$w_t - \mathcal{T}_{G,t} = p_{G,t}\ (1 - \alpha_e)\ \frac{E_{G,t}}{l_{G,t}} \tag{40}$$

3.3 Environment, Redistribution Policy and Inequality Measures

To complete the environmental module of our model, I proceed by defining the dynamics of emission accumulation, damage function and total abatement expenditure:

$$e_{s,t} = \eta e_{s,t-1} + e_t + e_t^{ROW}, \text{ where } e_t = e_{y,t} + e_{D,t}, \tag{41}$$

$$D_t = d_0 + d_1 e_{s,t} + d_2 {e_{s,t}}^2, \tag{42}$$

$$z_t = g(\mu_{y,t}) y_t(i) + g(\mu_{D,t}) E_{D,t}(i). \tag{43}$$

The pollution stock is a function of domestic emissions e_t and emissions from the rest of the world e_t^{ROW}; η is a parameter describing the decay rate of atmospheric pollution. Domestic emissions equal the sum of non-energy and dirty energy firms' GHG emissions; the damage D_t is a quadratic function of the pollution stock $e_{s,t}$; and z_t represents the total abatement spending from the two polluting sectors. The government is the central fiscal authority and collects taxes (carbon tax) from firms that pollute and redistributes revenues to households in the form of transfers ($\mathcal{T}_{HM,t}$ and $\mathcal{T}_{S,t}$) to offset the adverse effects of the Net Zero policy. Alternatively, they can be transferred to firms, in the form of subsidies to labor[8]. As specified before, these can take the form of labor cost subsidy to green energy producers ($\mathcal{T}_{G,t}$) or non-energy firms ($\mathcal{T}_{y,t}$). The public balance must hold, such that the sum of government consumption g_t and transfers and subsidies $\mathcal{T}_t$ does not exceed total tax revenues, as follows:

$$g_t + \mathcal{T}_t = \sqcup_t + \tau_{y,t} e_{y,t} + \tau_{D,t} E_{D,t}, \tag{44}$$

[8]Other type of firms incentives can include technology subsidies to increase productivity or substitutability among inputs (reduce energy dependence), or to reduce the burden of abatement cost. Some of these alternatives will be explored later in an updated version of the paper.

$$(1-\sigma_{HH})\mathcal{T}_{F,t} + (\sigma_{HH})\mathcal{T}_{HH,t} = \sigma_{tr}\left(\tau_{y,t}e_{y,t} + \tau_{D,t}E_{D,t}\right), \tag{45}$$

$$\mathcal{T}_{HH,t} = (\sigma_{HM})\mathcal{T}_{HM,t} + (1-\sigma_{HM})\mathcal{T}_{S,t} \tag{46}$$

$$\mathcal{T}_{F,t} = (\sigma_G\mathcal{T}_{G,t} + (1-\sigma_G)\mathcal{T}_{y,t} \tag{47}$$

The parameter σ_{tr} takes value 1 when carbon tax revenues are redistributed in forms of transfers or subsidies, 0 otherwise (dead weight loss in the form of public consumption). The parameter $\sigma_{HH} \in [0,1]$ indicates the subject of redistribution: 0 when it is firms (subsidies), 1 when it is households (transfers). These are further subdivided into subcategories. σ_{HM} is a weighting parameter that takes the value $[0,1]$, where 1 indicates that all transfers flow to HM households, 0 to S ones. $\sigma_G \in [0,1]$ equals 1 when all subsidies target green energy producers, 0 when they target non-energy ones.

A popular measure to quantify income inequality among individuals is the Gini coefficient. Gini is equal to zero in case of perfect equality, 1 in case of perfect inequality. In addition to income inequality, I measure consumption gap x_S/xHM, so that the effectiveness of redistribution policies can be quantified. Given the presence of two representative households in our model, the income Gini takes the following form:

$$G_t = \frac{1}{n}\left(n + 1 - 2\left(\frac{n\ y_{HM,t} + (n-1)y_{S,t}}{y_{HM,t} + y_{S,t}}\right)\right) \tag{48}$$

where G is the Gini coefficient, n the number of households groups, $y_{HM,t}$ and $y_{S,t}$ represents HM and S income, respectively.

3.4 Market Clearing

The labor market is not perfectly flexible. The elasticity of substitution between sector specific labor is higher then one but small. This results in the loss of a small portion of the resource when assigned to a new sector. Labor demand has to match total labor supply, equal to the weighted sum of households supply, where Δ is the share of HM families.

$$\left(l_{y,t}^{1+\phi_h} + l_{D,t}^{1+\phi_h} + l_{G,t}^{1+\phi_h}\right)^{\frac{1}{1+\phi_h}} = \Delta l_{HM,t} + (1-\Delta)l_{S,t} \tag{49}$$

Capital market is flexible and clears as follows:

$$k_t = k_{y,t} + k_{D,t} + k_{G,t}. \tag{50}$$

Energy total production must equal energy demand for consumption and production purposes

$$E_t = E_{c,t} + E_{y,t} \tag{51}$$

Both energy and non-energy goods' total consumption is given by:

$$E_{c,t} = \Delta E_{c,HM,t} + (1-\Delta) E_{c,S,t} \tag{52}$$

$$c_t = \Delta c_{HM,t} + (1-\Delta) c_{S,t} \tag{53}$$

Hence, aggregate consumption reads:

$$x_t = \Delta x_{HM,t} + (1-\Delta) x_{S,t} \tag{54}$$

3.5 Nominal frictions

In the model described so far, firms operate in a perfectly competitive market and prices are fully flexible. I now introduce the notation for monopolistic competition, sticky prices, and sticky wages. For the first two, I show only the equations for the non-energy sector. The same is true for energy intermediate producers; for brevity, the equations are not repeated explicitly here, as they follow the same logic.

I define the non-energy good y as an aggregation of intermediate inputs $y(i)$ produced by a continuum of monopolistically competitive firms indexed with i, with constant elasticity of substitution:

$$y_t = \left(\int_0^1 \left(y_t(i) \right)^{\frac{\xi_t - 1}{\xi_t}} di \right)^{\frac{\xi_t}{\xi_t - 1}}. \tag{55}$$

where ξ_t is the elasticity of substitution parameter and y_t is the Dixit-Stiglitz aggregator (Dixit and Stiglitz 1977). Nominal price rigidities are modeled by introducing quadratic adjustment costs $AC_t(i)$ à la Rotemberg (1983), which intermediate non-energy firms pay when adjusting their price with respect to the inflation target:

$$AC_t(i) = \frac{\phi_p}{2} \left(\frac{P_{y,t}(i)}{P_{y,t-1}(i)} - \bar{\pi} \right)^2 y_t P_{y,t}. \tag{56}$$

where ϕ_p is an adjustment cost parameter.

From the FOC with respect to price $P_{y,t}(i)$, I obtain the non-energy good Phillips curve:

$$\pi_{y,t}\left(\pi_{y,t}-\bar{\pi}\right)=\beta\mathbb{E}_t\left[\frac{\lambda_{t+1}}{\lambda_t}\frac{y_{t+1}}{y_t}\pi_{y,t+1}\left(\pi_{y,t+1}-\bar{\pi}\right)\right]$$
$$+\frac{\xi_t}{\phi_p}\left[\frac{mc_{y,t}}{p_{y,t}}-\frac{\xi_t-1}{\xi_t}+\tau_{y,t}(1-\mu_{y,t})\gamma_y+\theta_1{\mu_{y,t}}^{\theta_2}\right], \tag{57}$$

The inflation level for HM and S price index and the headline inflation π_t are as follows

$$\pi_{HM,t}=\pi_t\frac{p_{HM,t}}{p_{HMt-1}} \tag{58}$$

$$\pi_{S,t}=\pi_t\frac{p_{St}}{p_{St-1}} \tag{59}$$

$$\pi_t={\pi_{HM,t}}^{\Delta}{\pi_{S,t}}^{1-\Delta}. \tag{60}$$

The presence of price rigidities requires modeling the policy function adopted by the central bank in order to choose the value of the instrument (interest rate) to contrast inflation. In this case, the central bank follows a simple feedback rule of the Taylor (1993) rule class, as follows:

$$\frac{r_t}{\bar{r}}=\left(\frac{r_{t-1}}{\bar{r}}\right)^{\rho_m}\left[\left(\frac{\pi_t}{\bar{\pi}}\right)^{\phi_\pi}\right]^{1-\rho_m}, \tag{61}$$

where $\bar{r}$ and $\bar{\pi}$ represent the corresponding Ramsey steady state of the nominal interest rate and inflation; ρ_m denotes the degree of monetary policy inertia; ϕ_π denotes the response of the interest rate to the inflation gap[9].

Individual labor supply varieties are aggregated using the Dixit-Stiglitz function.

$$l_{j,t}=\left(\int_0^1\left(l_{j,t}(i)\right)^{\frac{\xi_W-1}{\xi_W}}di\right)^{\frac{\xi_W}{\xi_W-1}}, \quad \text{and} \quad j\in\{HM,S\}. \tag{62}$$

where ξ_W is the elasticity of substitution between individual labor supply. The latter is defined as a function of individual to aggregate wage share

$$l_{j,t}(i)=\left(\frac{w_{j,t}(i)}{w_{j,t}}\right)^{-\xi^W}l_{j,t}, \tag{63}$$

[9]For simplicity, I abstract from policy reaction to output gap variations.

such that the aggregate intermediate wage reads

$$w_{j,t} = \left(\int_0^1 w_{j,t}(i)^{1-\xi_W} di \right)^{\frac{1}{1-\xi_W}}. \tag{64}$$

Again we introduce sectoral nominal wage rigidity in the form of quadratic adjustment costs à la Rotemberg:

$$AC^W_{j,t}(i) = \frac{\phi_W}{2} \left(\frac{W_{j,t}(i)}{W_{j,t-1}(i)} - \bar{\pi} \right)^2 l_{j,t} W_{j,t}, \tag{65}$$

which is added to the left-hand side of the budget constraint of both households (2 and 4). Here ϕ_W represents the nominal wage adjustment cost parameter. Households' utility maximization problem yields the following new FOC with respect to $w^j_t(i)$:

$$mrs_{j,t} = \frac{\psi_j \, l^{\varphi_l}_{j,t}}{\lambda_{j,t}} \tag{66}$$

$$\begin{aligned} {\pi^W}_{j,t} \left({\pi^W}_{j,t} - \bar{\pi} \right) =& \beta \frac{\lambda_{j,t+1}}{\lambda_{j,t}} \frac{l_{j,t+1}}{l_{j,t}} \frac{w_{j,t+1}}{w_{j,t}} {\pi^W}_{j,t+1} \left({\pi^W}_{j,t+1} - \bar{\pi} \right) \\ &+ \frac{\xi_W}{\phi_W} \left(\frac{mrs_{j,t}}{w_{j,t}} - \frac{\xi_W - 1}{\xi_W} \right), \end{aligned} \tag{67}$$

where:

$$\begin{aligned} {\pi^W}_{j,t} &= \frac{W_{j,t}}{W_{j,t-1}} \\ &= \frac{W_{j,t}}{p_t} \frac{p_t}{p_{t-1}} \frac{p_{t-1}}{W_{j,t-1}} \\ &= \frac{w_{j,t}}{w_{j,t-1}} \pi_t. \end{aligned} \tag{68}$$

and $mrs_{j,t}$ is the inverse of the marginal rate of substitution between consumption and leisure; ${\pi^W}_{j,t}$ is the household j wage inflation;

As is common practice in the neo-Keynesian DSGE literature, I assume that firms operate in a monopolistically competitive market and that prices are sticky. In the next section, I will show simulation results of a model inclusive of all the nominal rigidities described so far[10].

[10] A comparison between the baseline and the flexible prices model is provided in section 4.4.

3.6 Abatement and Carbon Tax path

In the short run business cycle analysis, the economy is hit by an exogenous carbon tax shock. The tax evolves following an AR(1) process:

$$\ln \tau_{s,t} = \rho_\tau \ln \tau_{s,t-1} + (1 - \rho_\tau) \ln \overline{\tau_s} + e_{\tau,t}, \quad \text{where} \quad s = [y, D] \tag{69}$$

$\overline{\tau_s}$ is the steady state level of emission tax in sector s and e_τ is the exogenous carbon tax shock.

For the perfect foresight analysis, I follow the approach adopted by Ferrari and Nispi Landi (2023) to define the abatement and carbon tax path. I set ex ante the initial abatement level μ_D and μ_y at zero (year 2020), and the final level at 1 (year 2050), corresponding to a 100% reduction in total emissions. Additionally, I define the intermediate targets for the year 2030 (55%) and 2040 (90%), in line with the GHG emission abatement policy adopted by the EC. I then calculate carbon taxes τ_y and τ_D ex post. Carbon taxes grow linearly between targets for a total of 120 quarters (30 years) until the net zero target is reached. After that, the abatement level and the carbon tax remain constant.

3.7 Calibration

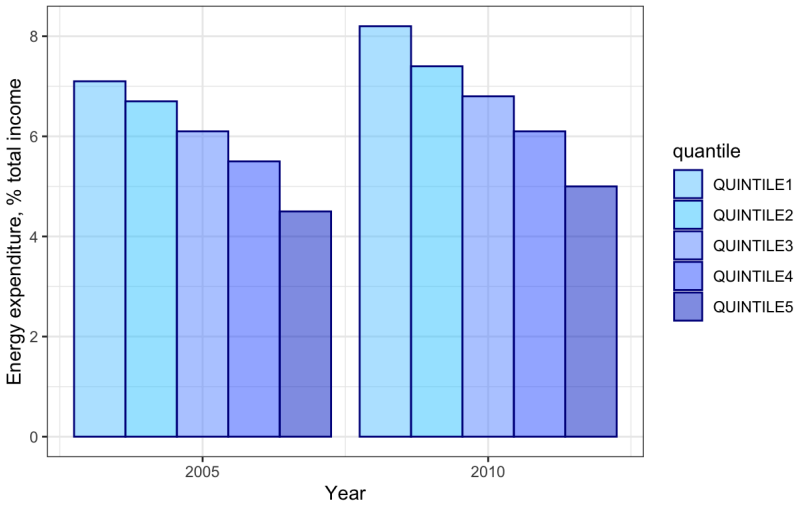
The model is calibrated to EU data at a quarterly frequency. Data on households income/wealth distribution and consumption habits are taken from the EU Statistics on Income and Living Conditions (EU-SILC) for the aggregate EU-27. The share of HM households corresponds to the bottom two income quantiles of the population, who hold almost zero net wealth and is equal to 40% of the population. From the Household Final Consumption Expenditure database[11] I derive also the parameters governing the basket composition of the two households groups. For the analysis, data from the 2010 EU-27 Household Budget Survey (HBS) on the Structure of Consumption Expenditure by Income Quintile are used[12]. Specifically, the focus is on expenditure within the category "Electricity, gas, and other fuels." This category is significant not only because it constitutes a substantial portion of household

[11] Eurostat's annual data on Household Final Consumption Expenditure, categorized by COICOP (Classification of Individual Consumption by Purpose), provides a comprehensive analysis of household spending across the EU. COICOP categorizes expenditures into various divisions, allowing for detailed insights into how households allocate their financial resources among different goods and services.

[12] The 2010 data for the EU-27 are comparable to the German and other major European countries' survey data from 2015 or similar to the 2020 survey, ensuring the relevance and validity of the analysis.

spending but also because it is central to examining how increases in carbon taxes can distort prices in this sector and impact households that spend a higher proportion of their income on these goods. What the data show is that household consumption for emission-intensive goods (mainly electricity, gas and other fuels) varies with changes in household income and wealth. The graph in figure 4 shows how households in the lowest quantile of the income distribution consume about twice the amount consumed by households in the highest quantile, as a percentage of their total income.

Figure 4: Electricity, Gas and Other Fuels Consumption Expenditure by Income Quantile, EU-27, %



Source: Eurostat

HM consume 7.8% of their total income on energy, while this share decreases to 5.9% for S families, on average. Note that the distribution parameter γ_j is derived from the energy share value ω_j, following the re-parametrization approach proposed by Cantore and Levine (2012). The different elasticity of substitution parameters between energy and non-energy goods consumption are borrowed from Känzig (2023), assuming HM are more constrained in their consumption behavior. Other households' parameters are borrowed from Drygalla et al. (2018) who estimate a DSGE model using German data. Firms parameters are derived from Eurostat data on energy, labor and capital share of production of energy and non-energy sectors. The energy sector is relatively more capital intense ($\alpha = 0.37$ while $\alpha_E = 0.73$)[13]. Elasticity of substitution between dirty and green energy in the energy CES aggregator is

[13]Capital intensity is calculated from labor intensity in the energy sector and the rest of the economy (here non-energy sector). Labor intensity is the ratio of compensation per employee to gross value added (GVA), corrected for the employed-to-employee ratio to account for the self-employed.

taken from Hassler et al. (2021), who estimate a value equal to 10 (good substitutes). The elasticity of substitution between the capital/labor bundle and energy in the non-energy production function is provided by van der Werf (2008). Alternatively, this elasticity can be reduced to a value close to zero (0.02), as estimated by Hassler et al. (2021), indicating a much stronger dependence of production on the energy input which, although plausible in the short run, can be too much restrictive for a long run analysis. The share of renewable energy consumption in the EU is around 25%, has provided by Eurostat. From this, I derive the weighting parameter of renewable energy ν. In order to derive the emission intensity of the non-energy and dirty energy sectors, I first fix the steady state of the pollution stock to 877.56 (GtG in 2020) and the volume of emissions from the rest of the world to be equal to 10 times the emissions from the EU. I set the share of emissions from the energy sector Q_E to 80%, reflecting emissions from energy consumption rather than production alone. This calibration aligns with Eurostat data, where emissions directly attributable to energy production account for 30%, but emissions from energy combustion – dependent on energy consumption –constitute 80% of total emissions. Thus, this approach better captures the broader impact of energy use on emissions. The amount of energy consumed by households Q_{Ec} is equal to 28% of total energy production. The resulting emission intensities from non-energy and dirty energy production are 0.043 and 1.423, respectively. For other environmental related parameters, I use the parametrization adopted in Gibson and Heutel (2023).

Table 1: Model parameters

Parameter	Description	Value	Source
Households			
β	Discount factor	0.995	Drygalla et al. (2018)
φ_c	Inverse elasticity of intertemporal sub.	1.5	–
φ_l	Inverse Frisch elasticity	1.5	–
φ_h	Inverse elasticity of labor sub. between sectors	1.5	–
ξ_w	CES parameter of labor supply	6	Standard value
ϕ_w	Wage adjustment cost	59.113	Implied from θ_c (Ascari and Rossi 2012)
ϵ_{HM}	Elasticity of subs energy/non-energy good, HM	0.05	Känzig (2023)
ϵ_S	Elasticity of subs energy/non-energy good, S	0.275	–
γ_{HM}	Distribution parameter HM	0.0778	Energy share $\omega_{HM} = 7.8\%$, EU-SILC
γ_S	Distribution parameter S	0.0599	Energy share $\omega_S = 5.9\%$, EU-SILC
ϕ_i	Investment adjustment cost	6	Standard value
Δ	Share of HM households	40%	–
Firms			
ξ_y	Elasticity of sub. between VA and energy	0.38	van der Werf (2008)
ξ	Elasticity of sub. between intermediate goods	6	Standard value
α	Share of capital in value added	0.37	Eurostat
$1-\upsilon$	Share of energy in non-energy production	0.13	–
θ_c	Calvo price parameter	0.75	Standard value
ϕ_p	Price adjustment cost	59.113	Implied from θ_c (Ascari and Rossi 2012)
χ	Elasticity of sub. between energy sources	2	Standard value
ι	Share of renewable energy	0.25	Eurostat
ν	Weighting parameter of renewable energy	0.215	Implied from ι
α_E	Share of capital in energy production	0.73	–
Q_{Ec}	Share of energy used for consumption by HH	28%	–
Q_E	Energy sector share of total emissions	80%	–
Environment			
γ_D	Energy sector emissions intensity	1.423	Implied from Q_E
γ_y	Non-energy sector emissions intensity	0.043	Implied from Q_E
d_0	Damage function constant	-0.0076	Gibson and Heutel (2023)
d_1	Damage function linear parameter	8.1e-6	–
d_2	Damage function quadratic parameter	1.05e-8	–
θ_1	Abatement cost function coefficient	0.074	–
θ_2	Abatement cost function exponent	2.6	–
η	Pollution decay rate	0.9965	Allen et al. (2018)
Other			
ϕ_π	Mon. pol. response to inflation	1.5	Standard value
ρ_m	Monetary policy inertia	0.9	–
ρ_{tau}	Carbon tax shock inertia	1	–

4 Simulation

4.1 Carbon Shock and Business Cycle

In this section, I analyze the business cycle effect of a carbon tax shock in the full model with nominal rigidities. I simulate a permanent 10% increase in the carbon tax for both non-energy and dirty energy sectors. The carbon tax evolves according to eq.69. I differentiate between 4 different scenarios and compare the dynamics of the model. In the first scenario named *Equal policy*, the carbon tax revenues are equally redistributed to all households, according to their relative weight. In the *HM policy* scenario, all revenues are transferred to HM households. In the last two cases - *Y labor policy* and *Green labor policy* - the money collected are used to subsidies non-energy and green energy firms, respectively, according to the scheme described in previous sections.

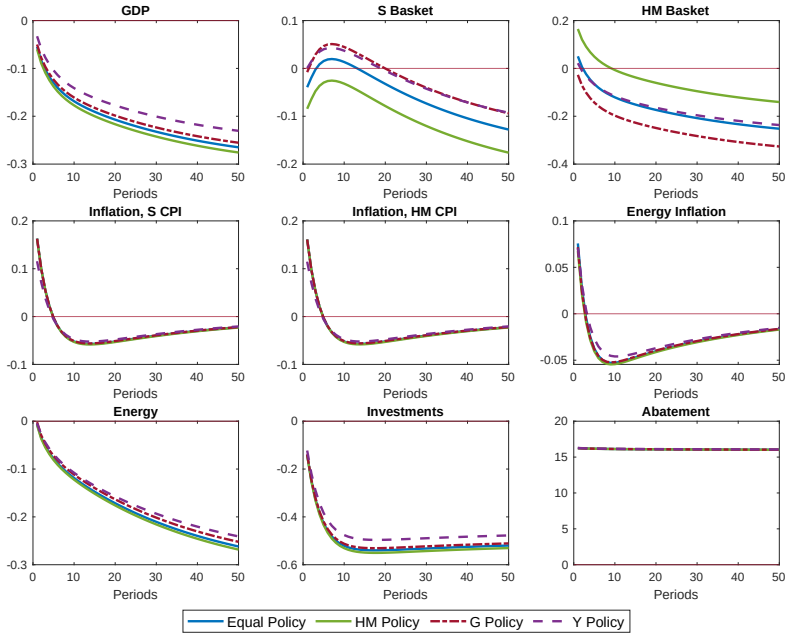
Inequality measures are presented in Figure 7. The top row of both panels shows the labor supply of the two household groups, while the bottom left figure plots changes in the Gini coefficient, and the bottom right figure illustrates the consumption gap under the different scenarios. A total redistribution of tax revenues to HM households alone achieves the greatest reduction in the income Gini coefficient, which remains below its steady-state value even beyond the simulation horizon (50 quarters). Equal redistribution to all households is also progressive but reduces inequality between the two groups to a lesser extent. The two firm subsidy programs are even less effective in addressing income inequality. In terms of the consumption gap, a total transfer to HM agents is again the most progressive in the short run. However, this effect reverses after approximately a year, as the consumption gap widens in all four scenarios following an initial slump. Redistribution exclusively to green firms is the most regressive, as it fails to mitigate the consumption gap effectively.

For all the different scenarios, the positive shock on carbon taxes has a direct impact on production costs for both sectors (y and E_G). This is reflected in the increase in energy inflation as well as the CPI for both households. As energy prices rise, energy demand falls. The contraction in net GDP (total output minus abatement and price/wage adjustment costs) is significant and persistent, around 0.3%. The largest contraction is observed in the case of redistribution to HM households, as they reduce their labor supply. The response of energy prices during the transition, while noticeable, remains moderate relative to the 10% increase in the carbon tax that directly affects dirty firms' costs. One key factor is that dirty and green energy are imperfect substitutes, meaning that changes in dirty energy prices and production cannot be fully or immediately offset by green energy adjustments. This constraint amplifies the persistence of price dynamics, particularly given the reliance of non-energy production on energy inputs. Additionally, the relatively low consumption elasticity of energy, especially for HM households, implies that energy demand remains relatively high despite price increases.

The higher energy price increases the marginal cost for non-energy producers, which are forced to reduce wages and capital remuneration. Labor subsidies to the non-energy sector alleviate the drop in wages, allowing firms to demand relatively more labor at the expense of the energy sector. This explains why, in this scenario, we observe the lowest decline in GDP. In all scenarios, capital and labor flow from the dirty to the green sector. As expected, with green firms being subsidized, green energy production increases the most. Also, firms' emissions are 3% lower, and total abatement costs increase by 15%.

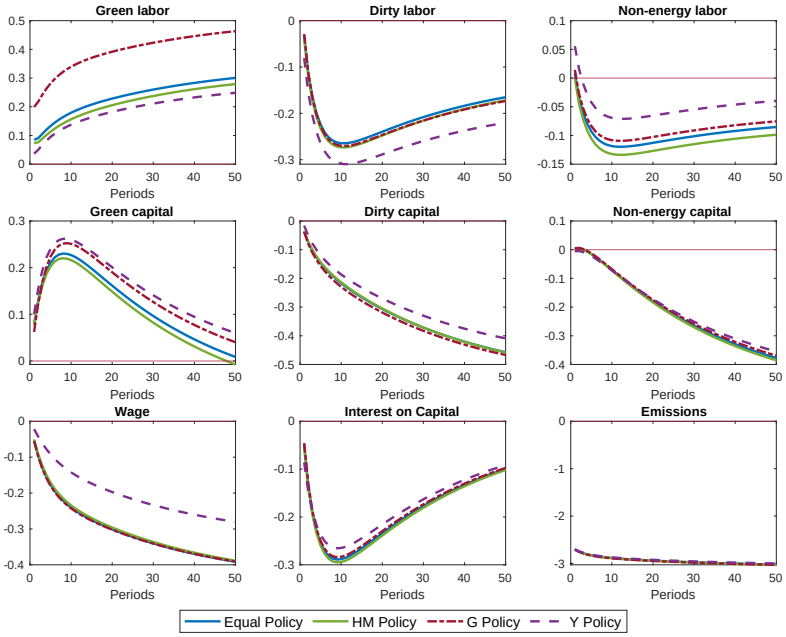
Interest on capital drops with a delay, following a U-shaped pattern, due to investment costs. Savers' consumption is strongly affected by this, as they are the only owners of capital in the economy. Their consumption initially increases, benefiting from the redistributive effects of firm subsidies. However, after 10 to 20 periods, it slowly moves to negative territory. The largest decrease in consumption occurs when only HM families are targeted with consumption subsidies. The opposite is true for HM agents, who can temporarily increase their consumption only when receiving direct transfers from the government. This is also reflected in the labor supply across households. Savers' labor supply varies only modestly across scenarios, as they can save the extra income when wages and capital returns are relatively higher. Hand-to-mouth households, instead, permanently supply more labor when only firms are subsidized and less when receiving government transfers (up to -0.15%).

Figure 5: Carbon Shock



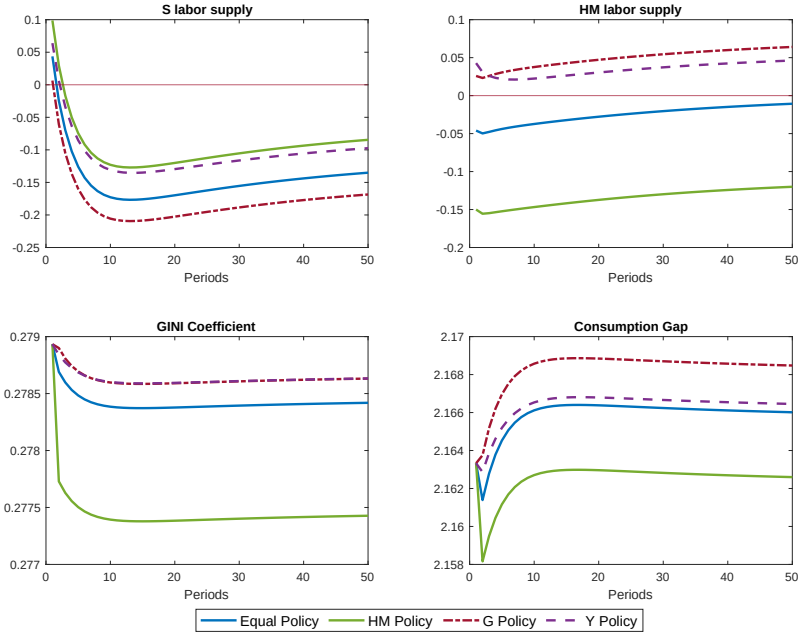
Note: IRF to a 10% increase in carbon tax. Variables expressed as percentage deviation from the initial steady state. Inflation expressed in annualized net level deviation.

Figure 6: Labor, Capital and Emissions, Carbon Shock



Note: IRF to a 10% increase in carbon tax. Variables expressed as percentage deviation from the initial steady state.

Figure 7: Labor Supply and Inequality Measures, Carbon Shock



IRF to a 10% increase in carbon tax. Labor variables expressed as percentage deviation from the initial steady state. Inequality measures expressed in levels.

4.2 Perfect Foresight Simulation

In this section, I simulate the long-term transition to an emission-free economy, where the government sets ambitious abatement targets, and the carbon tax – the shadow price of abatement – rises gradually over time. By the end of the transition, both non-energy and dirty energy firms fully abate their emissions. The policy is announced at the beginning of the simulation. Perfectly rational agents anticipate the full trajectory of the carbon tax, designed to achieve a 100% emissions reduction by 2050. The gradual increase in the carbon tax incentivizes firms to invest in abatement technologies as emissions become increasingly costly. This raises production costs permanently, leading to necessary cuts in wages and returns on capital (see figure 10).

The dynamics of energy prices reveal the interplay between supply constraints and demand adjustments. Initially, the presence of price rigidities dampens the response of energy prices despite the higher costs. The supply effect prevails. As agents internalize the tax trajectory, energy demand contracts sharply. Non-energy companies also reduce their demand for energy to cope with both the increase in its cost and the new tax on their own emissions. The price of energy thus falls to a low of -1.8%; a demand effect prevails. This deflationary phase persists until the intermediate emissions reduction target (90% reduction). The energy price plot has a u-shape, with a phase of deflation between about 2020 and 2040, and a phase of true inflation afterwards. Total energy prices only surpass pre-policy levels by 2050, driven by sustained inflationary pressures in the dirty energy sector. As before, the energy price dynamics are shaped not only by sticky prices but also by the imperfect substitutability between dirty and green energy. While energy production contracts by 9% and non-energy output falls by 12%, the investment component stabilizes by 2050 due to a rebound in interest rates on capital. Redistribution policies can partially mitigate these declines. For example, subsidies to non-energy firms help to attenuate the reduction in the energy price, maintain wages and limit reductions in output.

Redistribution policies play a critical role in shaping the dynamics of consumption, labor supply, and inequality. Both HM and saver households experience immediate reductions in consumption due to falling wages and capital returns. However, the impact varies significantly across redistribution schemes. Direct transfers to HM households delay their consumption drop by nearly a decade, providing a temporary buffer against income losses. Savers, in contrast, benefit more from firm subsidies, which stabilize wages and enable them to smooth

consumption through savings. By the end of the simulation, consumption declines are significant for both groups, with savers cutting back by 12% and HM households by 14%.

The labor supply response further underscores the differences between the two household groups. HM households, relying entirely on labor income, increase their labor supply in all scenarios except those involving direct transfers, which more than offset their income losses (see figure 11). Conversely, savers reduce their labor supply in the medium-term. This reduction is delayed, as savers initially increase their labor supply in anticipation of future wage cuts. The labor supply eventually converges back to steady-state levels, with more pronounced reductions under redistribution schemes that target savers or green firms[14].

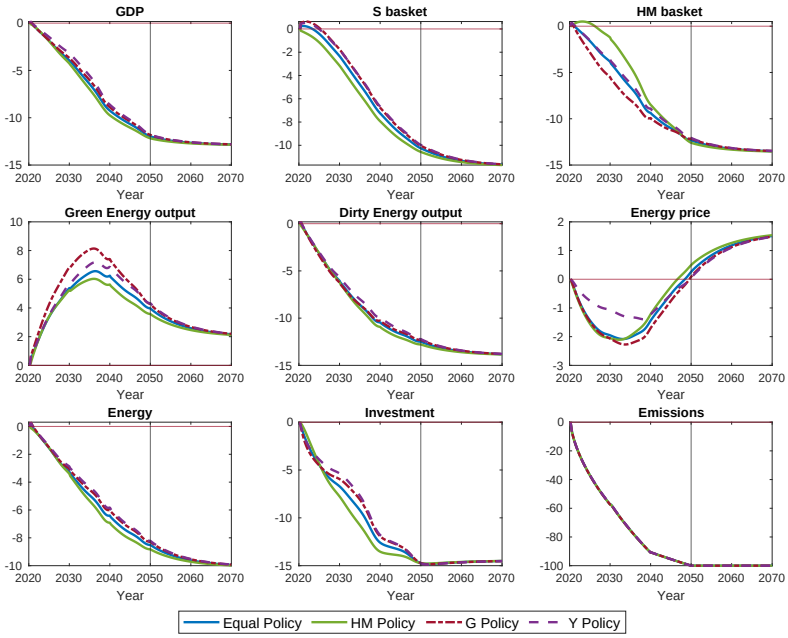
In terms of income inequality, all policies redistributing carbon tax revenues prove to be progressive (see figure 11. The largest reduction in the Gini coefficient is observed when only HM households benefit from subsidies. The HM policy is also the only progressive one in terms of the consumption gap. However, in this case, the effect is only temporary, as inequalities increase as the subsidy policy nears its end. In the other scenarios, the effect is slightly progressive (income inequality) or entirely regressive (consumption gap). In details, when redistributing carbon tax revenues to firms, both redistribution schemes are only slightly progressive, as measured by the Gini coefficient. The consumption gap measure is more ambiguous: S agents benefit the most from this kind of policy in terms of consumption in the short to medium run. They reduce investment, knowing wages are expected to be relatively higher in the future, while interest rate on capital is expected to collapse. Thus, they consume more compared to HM families. Inequality in consumption is especially exacerbated when subsidies are given to green energy firms, despite achieving the highest increase in green energy production (8%).

Breaking down energy prices into their green and dirty components (see figure 9) highlights the structural adjustments in the energy sector. Dirty energy prices rise modestly by 4% by 2070, despite collapsing demand, due to persistent abatement costs. In contrast, green energy prices fall by up to 6%, reflecting increased production driven by subsidies and resource reallocation. Capital and labor flow predominantly toward the green sector, resulting

[14]The labor supply of savers is affected by the so called income effect, as pointed out by Cantore and Freund (2021). Indeed, increased costs to the firm reduce profits, of which this group of households are beneficiaries (being the sole owners of intermediate firms). This might cause variations in their labor supply beyond expectations. To correct for this distortion, the authors opt for a different two-agent model, distinguishing between workers and capitalists. An alternative scenario with the same distinction will be provided in an updated version of the paper.

in an 8% increase in green energy production and a 14% reduction in dirty energy output. These trends underscore the effectiveness of green firm subsidies in accelerating the transition to greener energy sources. Upon reaching the net-zero target, the decline in consumption, energy production, and investment slows sharply. This stabilization is reflected in the energy price dynamics, where green energy prices stop falling, while dirty energy prices remain inflationary due to high abatement costs[15].

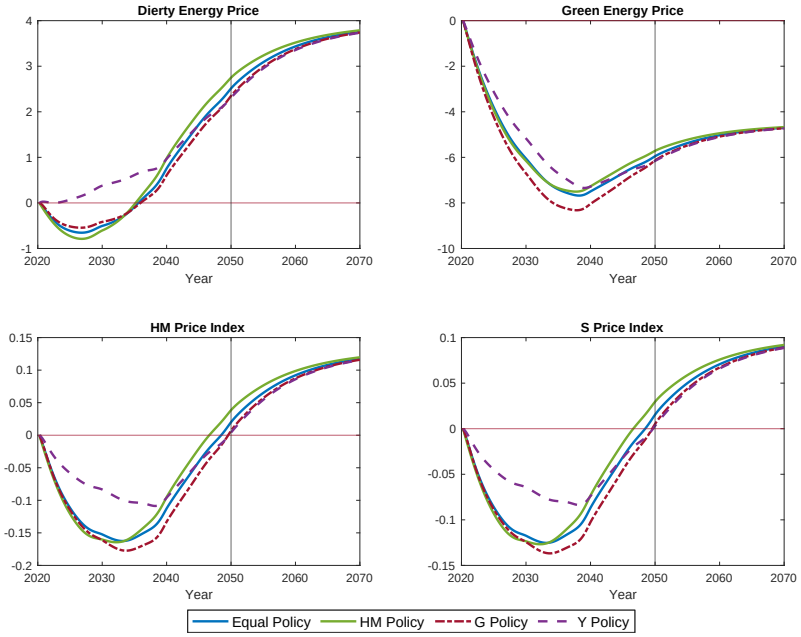
Figure 8: Net Zero Policy: Transition Dynamics



Note: variables expressed as percentage deviation from the initial steady state.

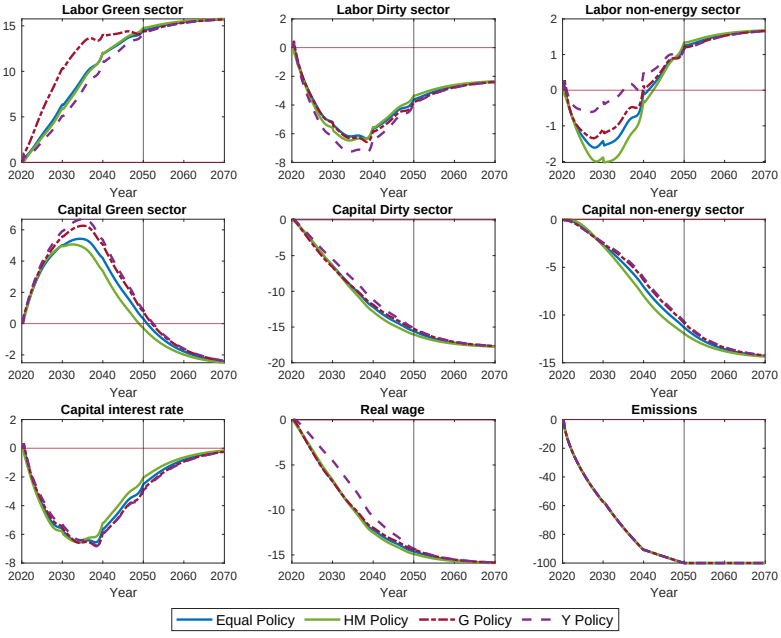
[15]Although firms no longer pay carbon taxes upon achieving net-zero emissions, the costs associated with abatement persist, influencing price dynamics.

Figure 9: Energy Prices, Transition Dynamics



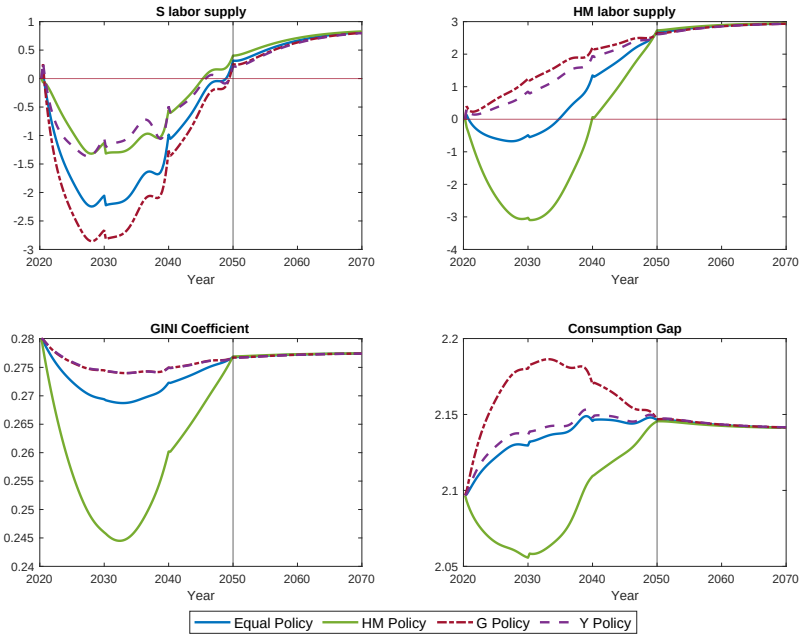
Note: variables expressed as percentage deviation from the initial steady state.

Figure 10: Labor, Capital and Emissions, Transition Dynamics



Note: variables expressed as percentage deviation from the initial steady state.

Figure 11: Labor Supply and Inequality Measures, Transition Dynamics

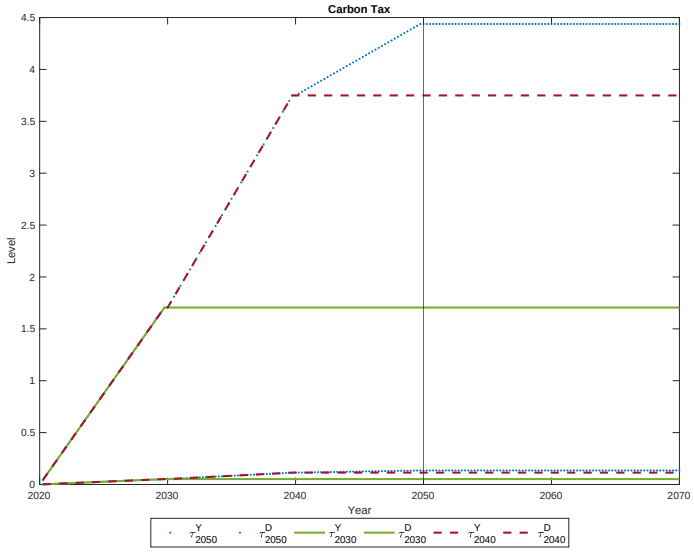


Note: labor variables expressed as percentage deviation from the initial steady state. Inequality measures expressed in levels.

4.3 Perfect Foresight with Expectation Errors

In the standard perfect foresight scenario, agents are initially surprised by the announcement of emission reduction targets at $t = 1$. From that point onward, they rationally anticipate all future emission cuts and the associated costs, which are captured in the carbon tax. In contrast, under the scenario with forecast errors, agents only receive updates on intermediate targets periodically. At $t = 1$, they are informed of a 55% emission reduction by 2030, and they believe that once this target is achieved, the tax will not increase further. However, at $t = 41$ (2030), a new target (90% reduction by 2040) is announced, resulting in an additional increase in the carbon tax. This same surprise effect occurs when reaching the 2040 target ($t = 81$), when the final goal of 100% reduction by 2050 is announced. The evolution of carbon taxes in the two sectors and for different time horizons is depicted in the figure12.

Figure 12: Carbon Tax at Different Time Horizons Targets



Note: Energy and Non-Energy Carbon tax expressed in real terms.

In this new scenario, agents are initially incorrect about the future shocks, and they correct their expectations over time. This setup introduces staggered reactions to shocks because agents initially operate under misinformed expectations. Here, the agents learn about the new path of the carbon tax at the same time that the shock hits, leading to smoother transitions as their new expectations align more closely with reality[16]. Their decisions reflect partial adaptation. Compared to the standard perfect foresight scenario, the expectation errors case tends to generate more dynamic adjustment paths, where agents may initially under – or overreact to shocks. The dynamics under this new scenario are displayed in details in the appendix D.1. A comparison between the baseline case and the model with expectation errors is presented in figures 13-14. For both models, the scenario considered is that of equal distribution of carbon tax revenues to households.

Output and investment are more volatile, as savers are forced to adjust their consumption/investment behavior to the new targets in response to the announcements. This leads to a sharper decline in investment, which by 2030 has fallen to twice the level observed in the baseline scenario. The rapid deterioration in investment contributes to a slower expansion of green energy production, which remains up to two percentage points lower between 2030 and

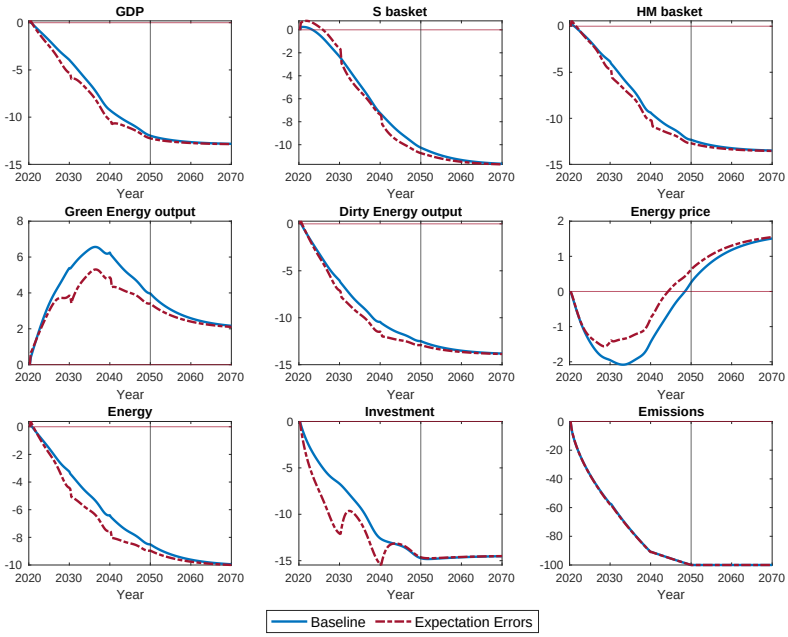
[16]The exact timing of when agents correct their expectations (before or during the shock) influences the smoothness of adjustment, especially in terms of how the economy absorbs the tax changes (both τ_Y and τ_D) and how quickly it transitions to the new equilibrium.

2050 compared to the baseline. In addition to the reduced capital turnover, higher energy prices in the medium term contribute to limiting the sector's growth.

While the consumption of savers remains higher during the first decade, supported by their ability to smooth consumption, their labor supply worsens significantly in the medium term (see figure 14). Wages are in fact at the same level as in the baseline case, but interest on capital in the short term rises slightly, providing more opportunities for consumption despite the lower labor supply. For HM households, the dynamics are less pronounced, as their consumption and labor supply are directly tied to their current income and are unaffected by new carbon tax announcements.

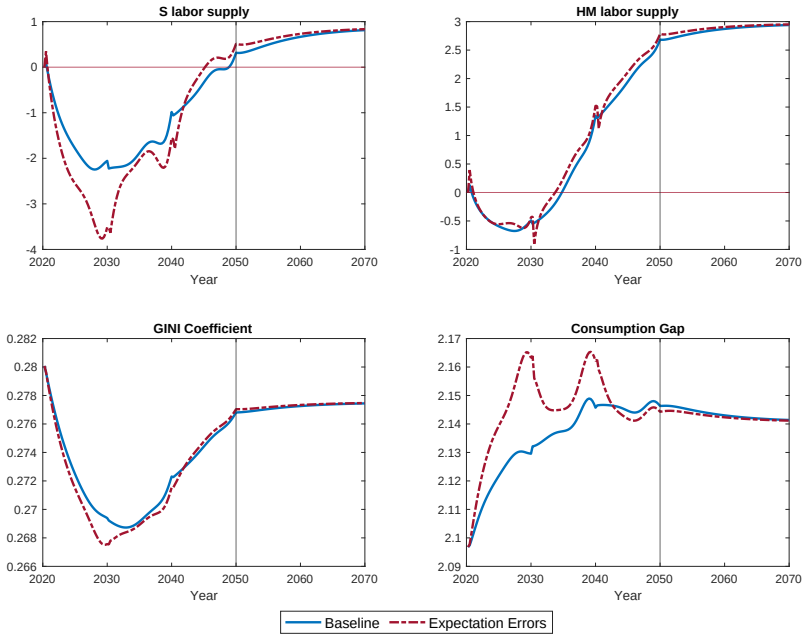
These differences result in a faster decline in energy and non-energy output in the medium term, although the overall decline converges to similar levels by the end of the simulation. Notably, negative inflation in the energy sector is less pronounced under expectation errors, and energy prices recover more quickly. In terms of distributional effects, the consumption gap between hand-to-mouth and savers worsens, reflecting greater disparities in consumption patterns. Overall inequality, as measured by the Gini coefficient, remains unaffected.

Figure 13: Net Zero Policy: Baseline vs Expectation Errors Model



Note: variables expressed as percentage deviation from the initial steady state.

Figure 14: Labor Supply and Inequality Measures: Baseline vs Expectation Errors Model

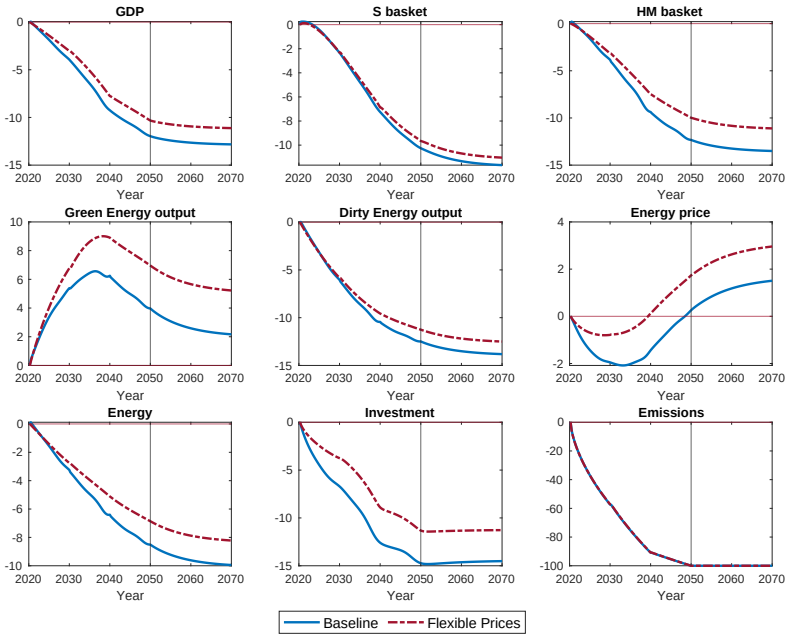


Note: labor variables expressed as percentage deviation from the initial steady state. Inequality measures expressed in levels.

4.4 Perfect Foresight with Flexible Prices and Wages

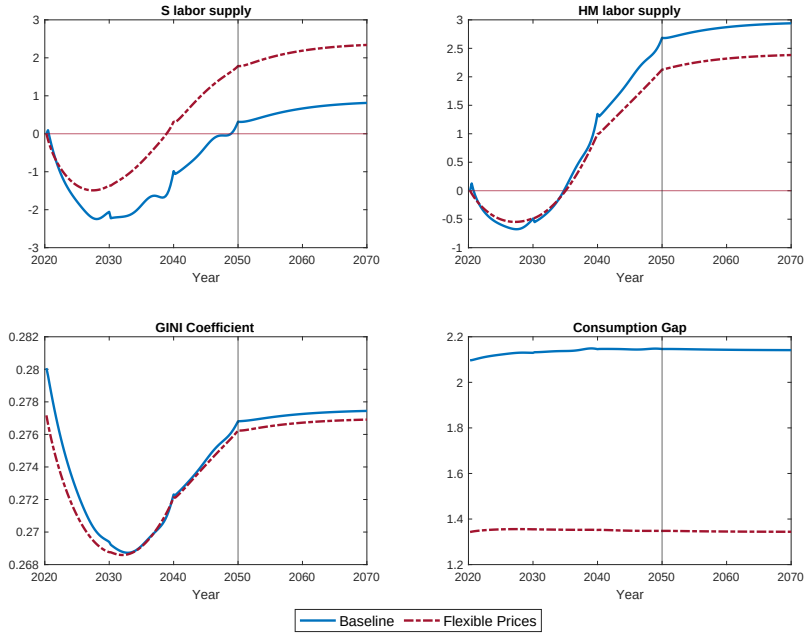
In the absence of nominal frictions (flexible prices and wages), there is a faster price adjustment and a consequent beneficial effect in terms of output. This is in fact greater in all sectors, despite the fact that the energy price, initially in deflation, rises 10 years earlier than in the baseline case. Consumption for both households is relatively higher. The difference is greater for HM households, while savers prefer to increase investment, which is reduced by (only) 10% (by 15% in the base case). Labor supply also recovers faster for S households. Income inequality and (especially) consumption gap are substantially lower in a flexible economy. A comparison between the baseline case and the model with flexible prices and wages is presented in figures 15-16.The detailed dynamics under this additional scenario are displayed in the appendix D.2.

Figure 15: Net Zero Policy: Baseline vs Flexible Prices Model



Note: variables expressed as percentage deviation from the initial steady state.

Figure 16: Labor Supply and Inequality Measures: Baseline vs Flexible Prices Model

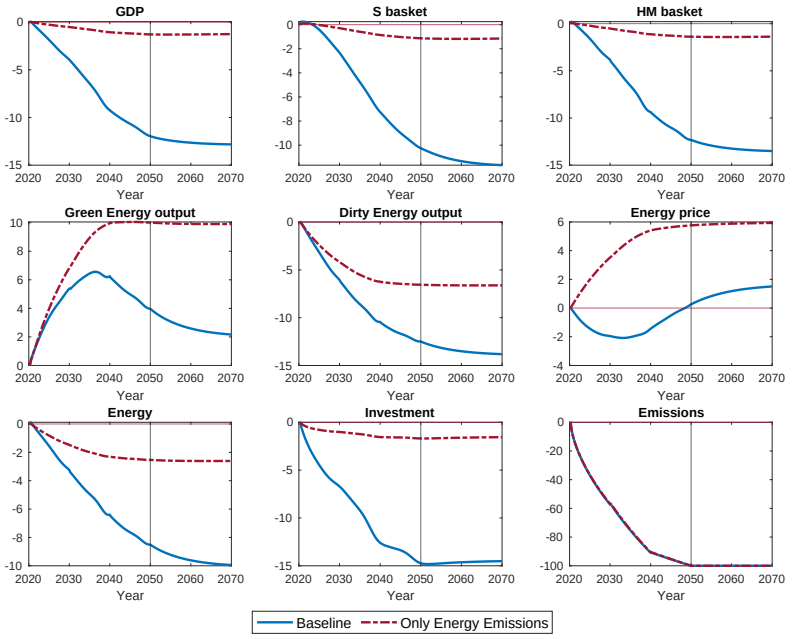


Note: labor variables expressed as percentage deviation from the initial steady state. Inequality measures expressed in levels.

4.5 Perfect Foresight with Only Energy Emissions

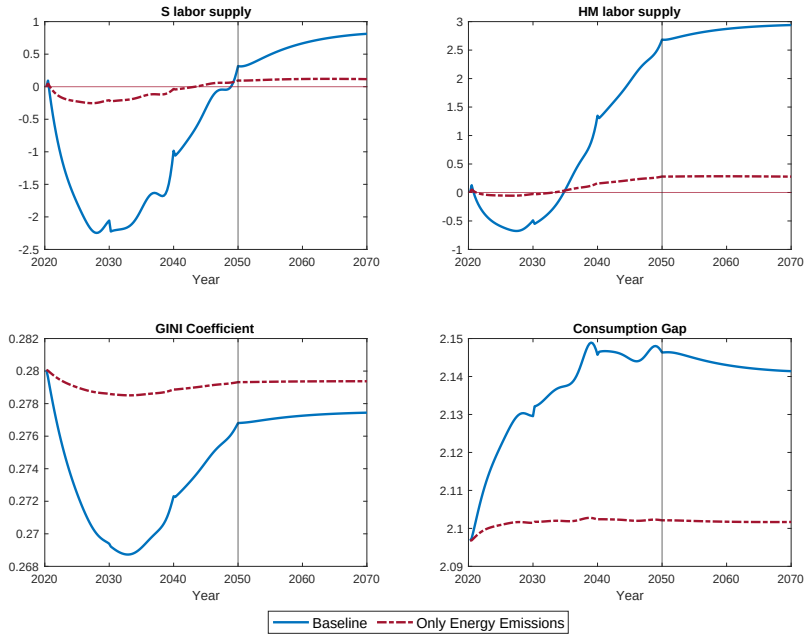
If we assume that emissions originate exclusively from fuel combustion and energy consumption, the model can be modified by setting non-energy emissions to zero. This adjustment produces dynamics that differ substantially from the baseline scenario. The smaller relative size of the energy sector implies that the impact of higher production costs on wages and capital returns is significantly reduced. Consequently, the decline in output is much smaller: GDP decreases by only 1.5%, and energy production falls by 2% (compared to 12% and 9% in the baseline scenario). This is accompanied by a more moderate drop in investment and a near-zero fluctuation in labor supply. However, this more muted response also dampens the reduction in inequality observed in the baseline case. The most significant difference lies in the trajectory of energy prices. Without a dominant demand effect to offset the impact of the carbon tax, energy prices rise sharply and stabilize more than 6% above their initial level (three times the increase observed in the baseline scenario). A comparison between the baseline case and the model without non-energy sector emissions is presented in figures 17-18.The dynamics under this scenario are displayed in the appendix D.3.

Figure 17: Net Zero Policy: Baseline vs Only Energy Emissions Model



Note: variables expressed as percentage deviation from the initial steady state.

Figure 18: Labor Supply and Inequality Measures: Baseline vs Non-Energy Emissions Model



Note: labor variables expressed as percentage deviation from the initial steady state. Inequality measures expressed in levels.

5 Conclusion

This paper examines the macroeconomic and distributional effects of carbon taxation in the EU, focusing on its short- and long-term impacts under various redistribution schemes. The analysis reveals that while carbon taxation is an indispensable component of the EU's climate strategy, it presents significant challenges, particularly in terms of its regressive effects on low-income households.

In the short-term simulation, when the economy experiences a permanent increase in the carbon tax, which acts as a supply-side shock, inflation rises and production declines. This dynamic is amplified by nominal rigidities, investment costs, and frictions in labor mobility. Initially, savers respond to the shock by supplying more labor and reducing consumption, while hand-to-mouth households, lacking savings, increase consumption. This situation is reversed as wages and returns on capital decline, allowing savers to smooth their consumption more gradually over time. The policy proves to be regressive, disproportionately burdening low-income households, although both groups of agents experience welfare losses after the shock. Redistribution schemes, whether in the form of transfers to households or subsidies to firms, mitigate income inequality to some extent. However, results for the consumption

gap are mixed: when hand-to-mouth households are the exclusive recipients of government transfers, income inequality is reduced most effectively, albeit temporarily.

In the long-run perfect foresight scenario, rational agents anticipate the trajectory of carbon taxes and the resulting income reductions, leading to deflationary pressures. Energy prices decrease temporarily as demand contracts, before rebounding in the later phases of the transition. All redistribution schemes demonstrate some degree of progressivity in terms of income inequality, as measured by the Gini coefficient. However, none fully addresses the consumption gap, which can worsen over time. When agents face forecast errors regarding emission reduction targets, the resulting uncertainty exacerbates fluctuations in investment and output. While this does not significantly alter income inequality, it intensifies consumption disparities, particularly for hand-to-mouth households.

The findings highlight the importance of complementing carbon taxes with carefully designed compensation mechanisms, such as targeted transfers to vulnerable households and subsidies for green firms. Additionally, complementary measures, including policies that reduce abatement costs and foster technological innovation, are essential to accelerating the transition while minimizing its adverse effects.

Future research should focus on exploring the interactions between carbon taxation, income inequality, and economic growth over extended time horizons, particularly in the presence of diverse household structures and varying degrees of policy credibility. Understanding these dynamics is critical for designing policies that balance environmental goals with social equity. A balanced approach that combines environmental sustainability with social justice will be crucial for the success of the EU's transition to a net zero economy.

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Appendix (WORK IN PROGRESS)

A E-DSGE Model Derivations

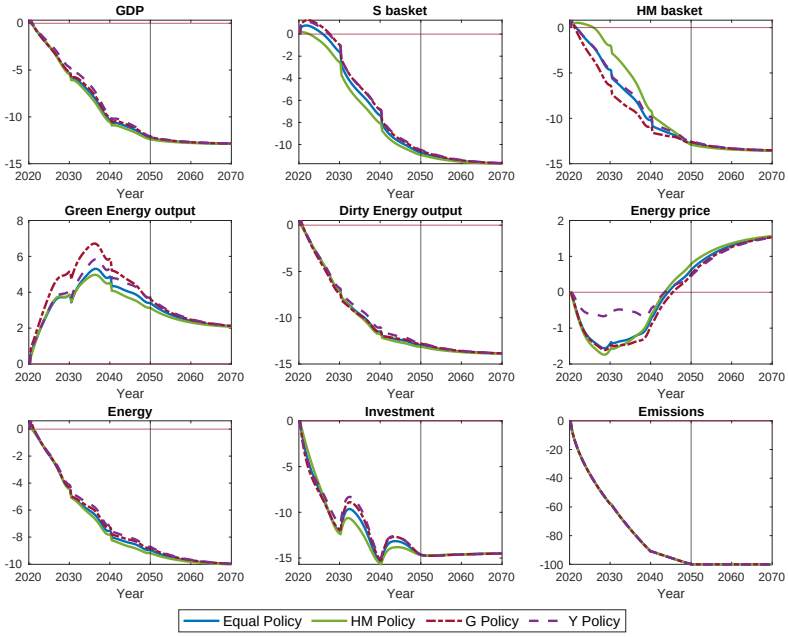
B E-DSGE steady state

C Sensitivity Analysis

D Additional figures: Perfect Foresight Simulation

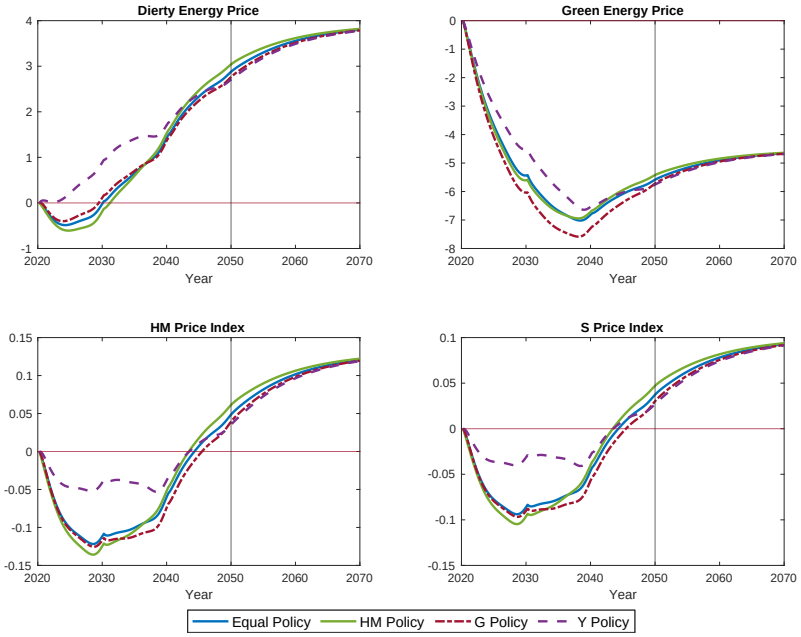
D.1 Expectation Errors

Figure 19: Net Zero Policy: Transition with Expectation Errors



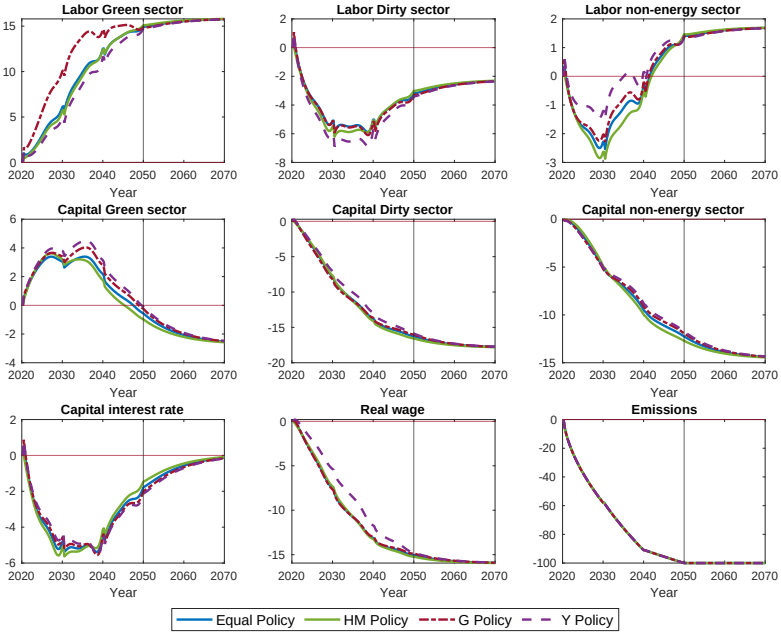
Note: variables expressed as percentage deviation from the initial steady state.

Figure 20: Energy Prices, Transition with Expectation Errors



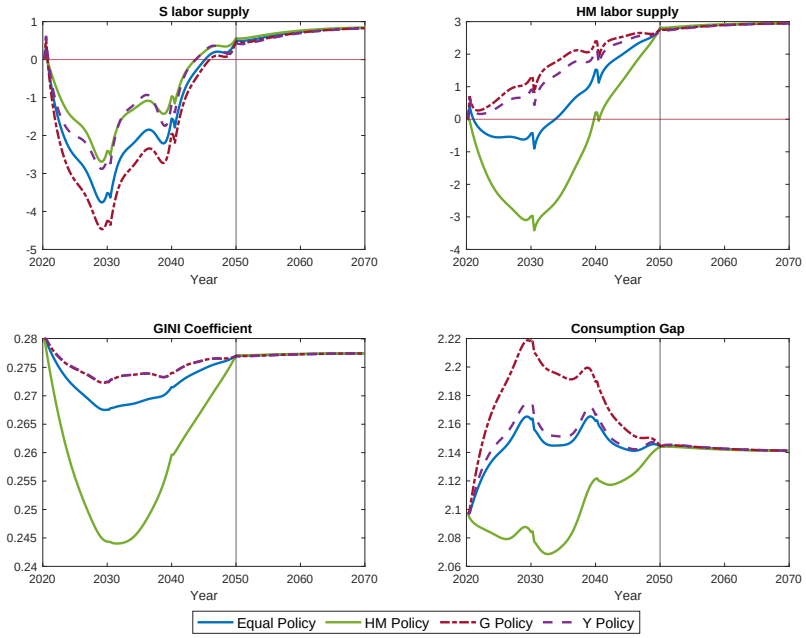
Note: variables expressed as percentage deviation from the initial steady state.

Figure 21: Labor, Capital and Emissions, Transition with Expectation Errors



Note: variables expressed as percentage deviation from the initial steady state.

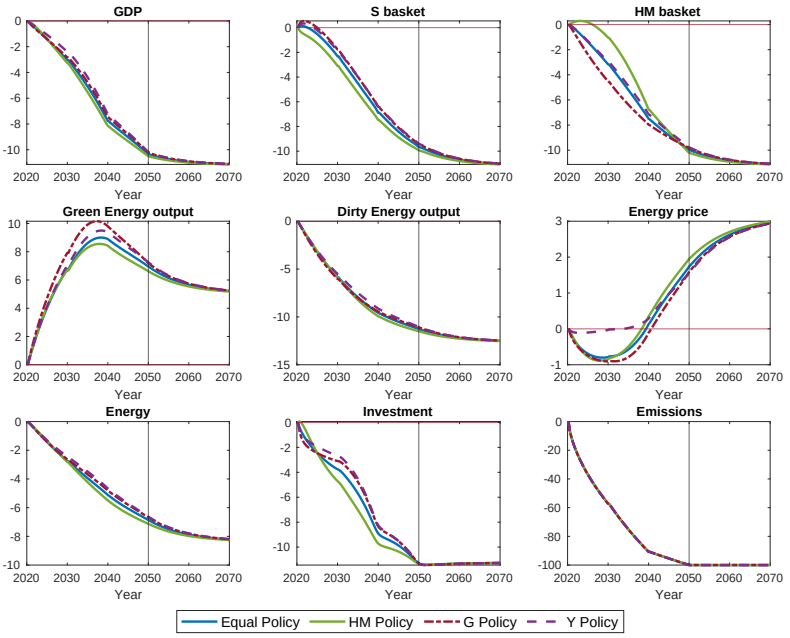
Figure 22: Labor Supply and Inequality Measures, Transition with Expectation Errors



Note: labor variables expressed as percentage deviation from the initial steady state. Inequality measures expressed in levels.

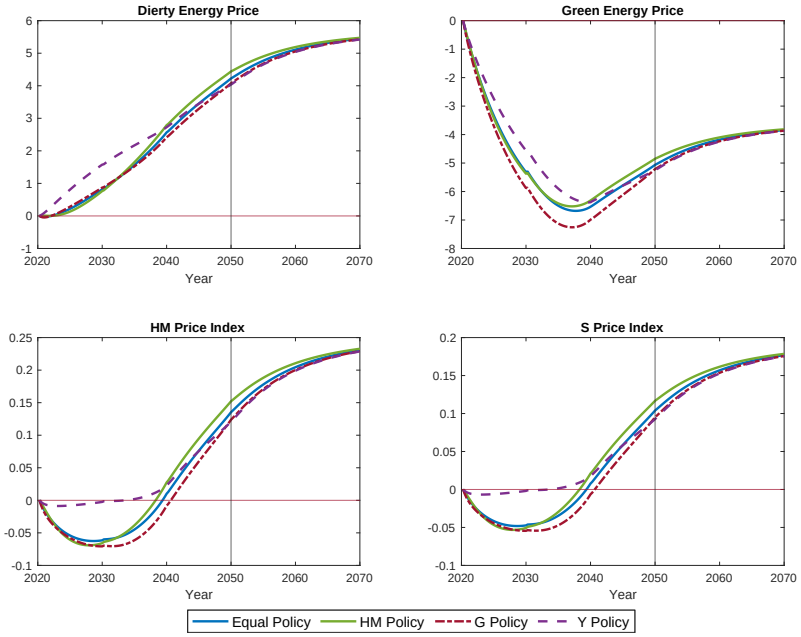
D.2 Flexible Prices

Figure 23: Net Zero Policy: Transition Dynamics



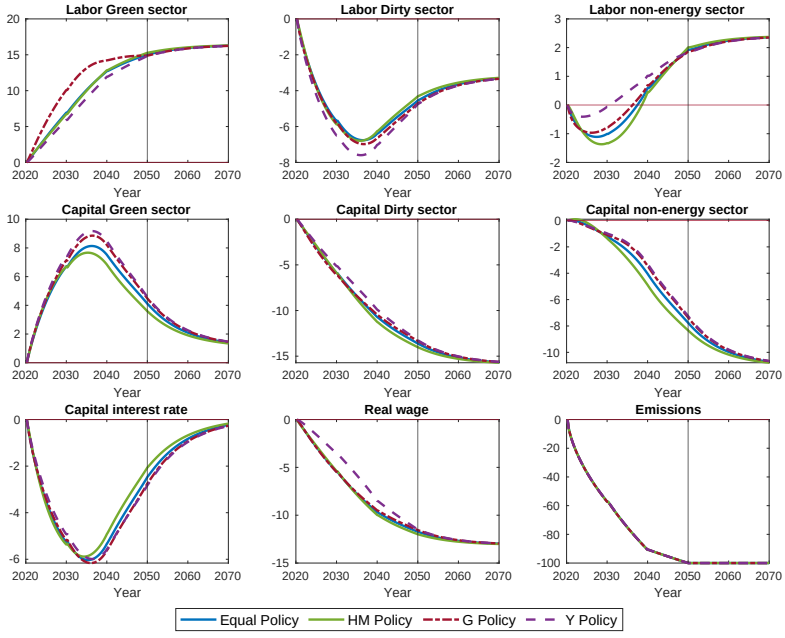
Note: variables expressed as percentage deviation from the initial steady state.

Figure 24: Energy Prices, Transition Dynamics



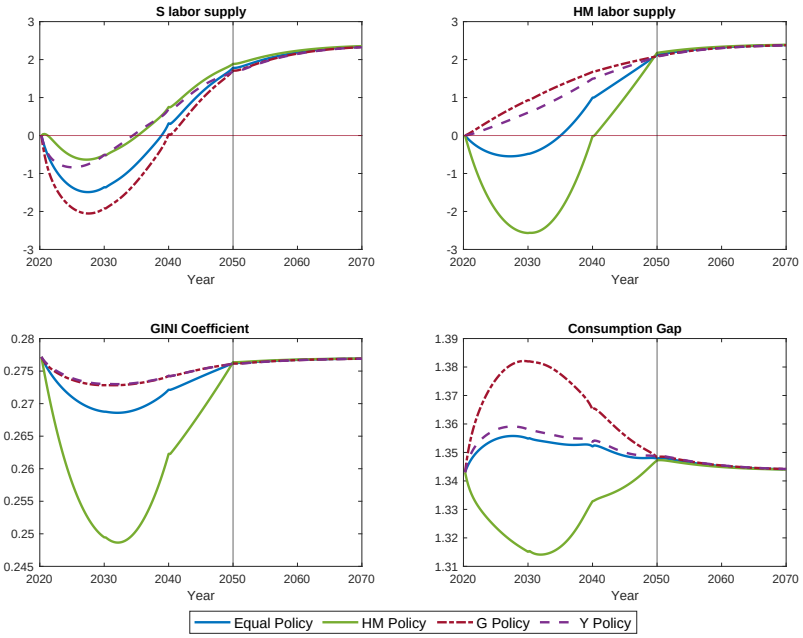
Note: variables expressed as percentage deviation from the initial steady state.

Figure 25: Labor, Capital and Emissions, Transition Dynamics



Note: variables expressed as percentage deviation from the initial steady state.

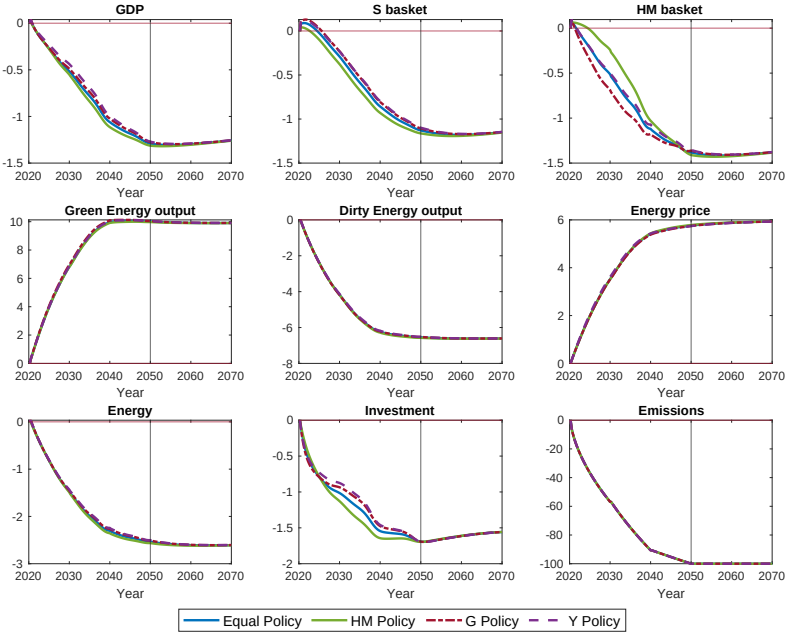
Figure 26: Labor Supply and Inequality Measures, Transition Dynamics



Note: labor variables expressed as percentage deviation from the initial steady state. Inequality measures expressed in levels.

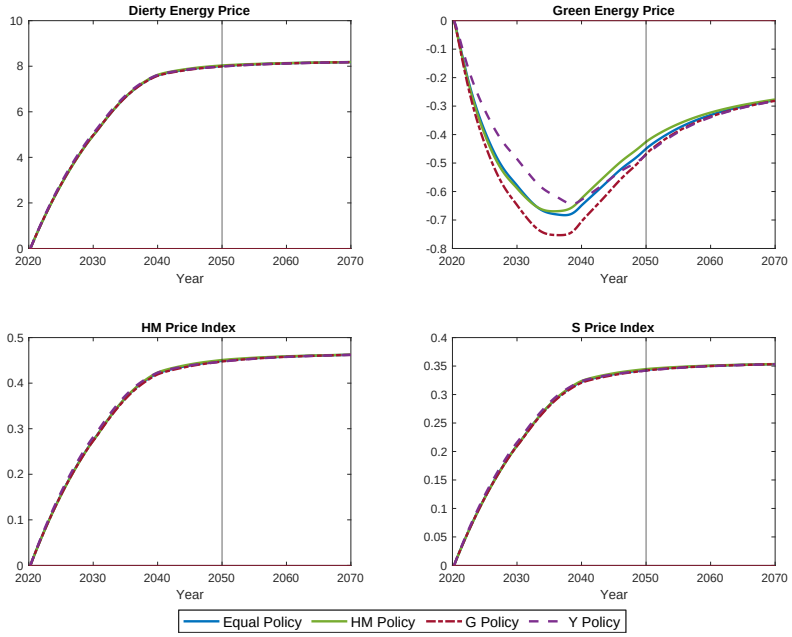
D.3 Only Energy Emissions

Figure 27: Net Zero Policy: Transition Dynamics



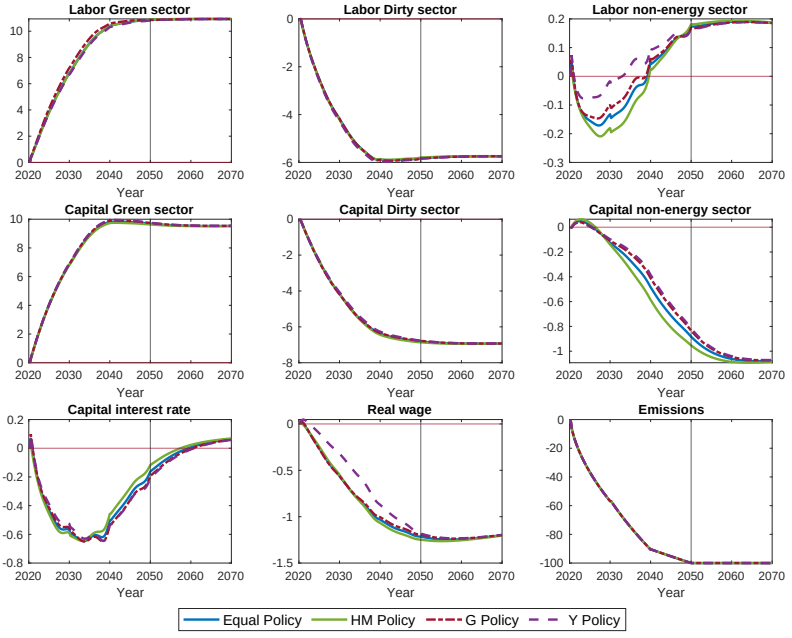
Note: variables expressed as percentage deviation from the initial steady state.

Figure 28: Energy Prices, Transition Dynamics



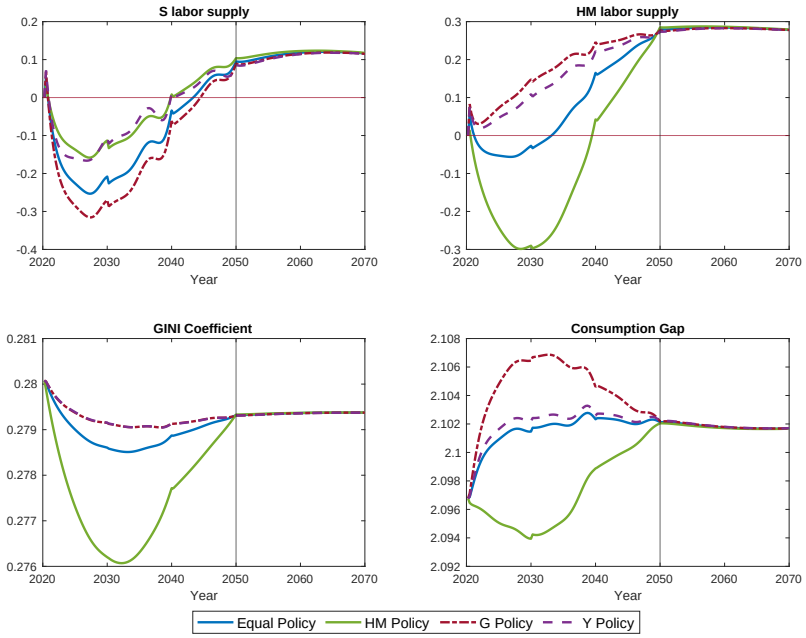
Note: variables expressed as percentage deviation from the initial steady state.

Figure 29: Labor, Capital and Emissions, Transition Dynamics



Note: variables expressed as percentage deviation from the initial steady state.

Figure 30: Labor Supply and Inequality Measures, Transition Dynamics



Note: labor variables expressed as percentage deviation from the initial steady state. Inequality measures expressed in levels.