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Transitioning to net-zero: macroeconomic implications and welfare assessment

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Transitioning to Net-Zero: Macroeconomic Implications and Welfare Assessment[*]

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Abstract

We assess the macroeconomic and welfare implications of carbon mitigation strategies using an environmental Dynamic General Equilibrium model. The economy uses energy from both green renewable technologies and fossil fuels. We set an emission reduction target in line with the Paris Agreement and analyze the welfare and macroeconomic impacts of various strategies, including (1) raising the domestic price of fossil fuels, (2) implementing a subsidy on green investment funded through lump-sum taxes, (3) imposing taxes on emissions with rebates to households, and (4) utilizing emission taxes to support green investment. Our model provides a framework for evaluating the welfare consequences of various carbon mitigation strategies, emphasizing the need to balance the short and long-term effects of incentives for investment and innovation in green technologies, as well as taxes and other policies designed to reduce carbon emissions.

Keywords: carbon emissions, green energy, brown energy, energy transition, welfare
JEL Classification: Q43, Q58.

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1. Introduction

The urgency of transitioning to a low-carbon economy cannot be understated, particularly in light of mounting evidence of climate change (IPCC, 2023). Aligned with the goals set forth in the Paris Agreement (UNFCCC, 2015), the International Energy Agency (IEA, 2020) has outlined a normative scenario aimed at achieving Net Zero Emissions (NZE) by 2050. Advanced countries, particularly EU countries, with their national and common policies and coordinated national energy and climate plans (NECPs), should be at the forefront of decarbonization. The effective implementation of economic policies designed to facilitate the energy transition will significantly shape the dynamics of these economies. As highlighted by Batten (2018), it is essential to analyze the economic consequences of carbon emission reduction policies, not in isolation but as part of a broader policy framework aimed at fostering economic growth.

This paper contributes to the existing literature exploring the relationships among technology, fiscal policy, and the macroeconomic and welfare consequences associated with the energy transition. To this end, we assess the transition towards a low-emissions economy using an environmental Dynamic General Equilibrium (eDGE) model. These models are specifically designed to capture the relationship between climate change and economic growth, drawing inspiration from earlier works such as Nordhaus (1991) (see Annicchiarico et al., 2021, and Annicchiarico et al., 2022, for two recent surveys).

Our model provides a framework for assessing the macroeconomic and welfare implications of different carbon mitigation strategies, highlighting the importance of balancing the short and long-term effects of incentives for investment and innovation in green technologies, taxes, and other policies aimed at reducing carbon emissions. In our model, the production of goods and services utilizes energy from either environmentally friendly renewable ("green") technologies or fossil fuels that generate CO2 emissions, commonly known as "dirty" or "brown" technologies. Energy producers employ specific capital to generate this input, resulting in CO2 emissions with different intensities depending on the use of these technologies.

By considering the more realistic case of emissions being dependent on a particular type of energy production, we enrich the relationship between carbon generation and aggregate output, allowing emissions reductions to be achieved not only by reducing output but also by changing the combination of inputs. In addition, the model takes into account the transformative potential of technological advances to reduce the prevalence of brown energy and improve the overall efficiency of the energy mix. This aspect of our research aligns with the works of Fried (2018) and Nakicenovic and Swart (2000). Furthermore, we acknowledge the pivotal role that investment in green energy capital plays as a key driver of this transition (see Jackson and Jackson, 2021).

As a numerical illustration and an example of our model's application, we calibrate it with data from the Spanish economy, which ranks among the four largest countries in the EU. Specifically, we set an emission reduction target consistent with the Paris Agreement and analyze the welfare and macroeconomic effects of different strategies, such as increasing the domestic price of fossil fuels, implementing a subsidy on green investment financed by lump-sum taxes, levying taxes on emissions rebated to households, and using emissions taxes to finance green investment. These policies are strategically designed to mitigate emissions and incentivize the widespread adoption of green technologies. In this context, our study aligns with recent literature, including Marron and Toder (2014), the International Monetary Fund (2019), Semmler et al. (2021), and Delgado-Téllez et al. (2022).

Our main findings can be summarized as follows. Front-loaded environmental policies intended to mitigate carbon emissions may prove effective in achieving the intermediate 2030 Green Deal target, although they are insufficient to meet the 2050 Net Zero Emissions (NZE) target without a substantial increase in welfare costs. Alternatively, green investment subsidies require more time to deliver a significant reduction in emissions compared to other policies. Contrary to other mitigation policies, subsidizing green investment leads to an increase in energy intensity per unit of output due to the upsurge in green energy production. A one-time, front-loaded increase of nearly 60% in fossil fuel prices to discourage their use achieves over 80% of the NZE target, although increasing fossil fuel prices incurs the highest welfare costs in both the transition to 2050 and in the long run. Emission taxes emerge as the most preferable policy in terms of welfare during the transition to 2050, although green investment subsidies yield substantial welfare gains in the very long run, even without a globally coordinated emission reduction policy. Reallocating revenues from carbon taxes toward green investment subsidies yields the most balanced welfare effect between the short and long run. To achieve the NZE target by 2050, we need a linear increase in emissions taxes to reach a level of 227 € per ton of carbon by 2050 and stabilize afterwards. The average welfare loss resulting from this policy stands at a manageable -0.44% in terms of equivalent consumption from 2019 to 2050, however, it rises to -19.11% in the very long run, covering the period from 2019 to 2200.

In the absence of an internationally coordinated strategy, the temperature is projected to increase by 1.8 degrees Celsius above pre-industrial levels by 2050 and by over 3.5 degrees Celsius by 2200. In a coordinated scenario the temperature remains below 1.5 degrees Celsius by 2050 and reverts to almost pre-industrial levels by 2200. The positive impact on welfare of a coordinated policy becomes evident, although it takes several decades to materialize. In the very long run, average welfare may increase by over 50% in terms of consumption between 2019 and 2200, as the world economy avoids the damages of climate change.

This paper is structured as follows: In Section 2, we provide a comprehensive overview of the model, emphasizing the role played by green and brown sources of energy at various stages of demand and production. Section 3 delves into our approach to selecting model parameters, with particular attention given to those governing utility, the damage function, emissions function, and abatement costs function. Section 4 presents the simulation exercises. We start by building our base scenario consistent with some recent trends and with the model equations, from which we derive both optimistic and pessimistic scenarios. Subsequently, we perform a numerical assessment of the effects of different mitigation strategies on emissions, macroeconomic performance, and welfare. This section also includes a sensitivity analysis encompassing scenarios without technological progress or with globally coordinated policies. Finally, Section 5 presents the main conclusions.

2. The Model

The economy operates by producing goods and services through the utilization of labor, capital, and energy. The production process is organized across distinct levels. At the bottom level, energy producers employ specific capital to generate energy, resulting in varying CO2 emissions, contingent on the use of green or brown technologies. Brown energy producers also engage in the importation of fossil fuel commodities at international market prices, which can fluctuate or be influenced by tariffs or subsidies. Companies have the option to invest in emission reduction, which incurs additional costs, and emissions can be subjected to taxation. Technological advancements in fossil fuel utilization aid in the economy's decarbonization efforts.

The subsequent level comprises energy suppliers, which procure both green and brown energy from producers, amalgamating them into a bundle sold to intermediate goods producers. The pricing of this energy bundle is contingent on the composition of energy sources. Progress in technology favoring green energy production plays a pivotal role in reducing carbon emissions.

At the intermediate non-energy production level, firms engage labor, capital, and energy from the energy bundle to manufacture a diverse range of goods under monopolistic competition. Each product variation faces a demand curve that slopes downward, while firms encounter costs related to price adjustments, resulting in price stickiness. Finally, at the topmost tier, firms aggregate various intermediate goods and market a standardized product for consumption, investment, and public spending. Technological advancements also influence overall productivity in final goods production.

Households contribute labor services, using their income to acquire consumption goods and invest in diverse capital goods. The government can enact mitigation strategies, such as subsidizing green investments, imposing tariffs on fossil fuel imports, or implementing emissions taxes. Government revenues can be redistributed to households through lump-sum transfers. Conversely, subsidies can be financed through lump-sum taxes levied on households.

Next, we provide an overview of our model and highlight the key decision problems faced by agents at each level of production. For a detailed account of the model equations, see Appendix A.

2..1 Households

The representative household in the model maximizes lifetime utility, which is determined by its consumption (c_t) and working hours (h_t). Households earn labor and capital income; the latter comes from renting out different types of capital to firms at rental rates r_t^f (with $f = g, b, y$ representing the rental rates for green, brown, and intermediate production capital), holding government bonds (r_t). As the owners of all firms in the economy, they also receive profits ($\Gamma_t^{v^g}$, $\Gamma_t^{v^b}$, and Γ_t^{y} respectively). After consuming and paying taxes (or receiving subsidies), households save their remaining income in government debt (b_t) and invest in three types of productive capital: capital for producing intermediate goods (k_t^y), capital for producing green energy (k_t^g), and capital for producing brown energy (k_t^b), subject to quadratic capital adjustments costs. The government has the option of subsidizing households' investment in green capital ($\tau_t^{i^g}$) and collects a lump-sum tax (or pays a subsidy) every period to balance its budget (τ_t^h).

The representative household solves the following problem:

$$\max_{\{c_t, h_t, i_t^y, i_t^g, i_t^b, k_t^y, k_t^g, k_t^b, b_t\}_{t=0}^{\infty}} \quad \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left(\frac{c_t^{1-\sigma}}{1-\sigma} - \kappa_L \frac{h_t^{1+\varphi}}{1+\varphi} \right) \qquad s.t \tag{1}$$

$$\begin{aligned} P_t c_t + P_t i_t^y + P_t(1-\tau_t^{ig}) i_t^g + P_t i_t^b + b_t = \\ r_t^y P_t k_{t-1}^y + r_t^g P_t k_{t-1}^g + r_t^b P_t k_{t-1}^b \\ + r_{t-1} b_{t-1} + P_t w_t h_t - P_t \tau_t^h \\ + P_t \Gamma_t^y + P_t \Gamma_t^{vg} + P_t \Gamma_t^{vb} \end{aligned} \tag{2}$$

$$k_t^y = (1-\delta_y) k_{t-1}^y + \left[1 - \frac{\kappa_I^y}{2} \left(\frac{i_t^y}{i_{t-1}^y} - 1 \right)^2 \right] i_t^y \tag{3}$$

$$k_t^g = (1-\delta_g) k_{t-1}^g + \left[1 - \frac{\kappa_I^g}{2} \left(\frac{i_t^g}{i_{t-1}^g} - 1 \right)^2 \right] i_t^g \tag{4}$$

$$k_t^b = (1-\delta_b) k_{t-1}^b + \left[1 - \frac{\kappa_I^b}{2} \left(\frac{i_t^b}{i_{t-1}^b} - 1 \right)^2 \right] i_t^b \tag{5}$$

where P_t (the numeraire) represents the price of the final good, so all relative prices are referred to this numeraire, and κ_I^f is a parameter that controls for the intensity of the capital adjustment costs.

2..2 Energy producers

Green and brown energies are produced by firms in competitive markets with specific capital using the following technology:

$$v_t^g = \varsigma_t^g \left(k_{t-1}^g \right)^{\alpha^g} \tag{6}$$

$$v_t^b = \left(k_{t-1}^b \right)^{\alpha^b} \left(m_t^b \right)^{(1-\alpha^b)} \tag{7}$$

where m_t^b refers to an energy commodity produced abroad (e.g., oil or gas) that is combined with capital and ς_t^g represents the efficiency of green energy production, with higher efficiency indicating that less capital is required to produce one unit of energy. This variable can change exogenously over time, and an increase in ς_t^g can be interpreted as a green-biased technological change (i.e. we normalize to one the efficiency in the production of brown energy). More specifically, we assume that ς_t^g evolves exogenously over time according to the equation:

$$\varsigma_t^g = \varsigma_0^g \left(1 + g_{\varsigma^g}\right)^t \tag{8}$$

Here, ς_0^g represents the initial calibrated value of the green energy production efficiency, and g_{ς^g} denotes its annual growth rate, reflecting exogenous technological progress biased towards green energy production.

We assume that period carbon emissions are an increasing function of the amount of brown energy produced,

$$e_t^b = \left(1 - \mu_t^b\right) \gamma_{1t}^b \left(v_t^b\right)^{1-\gamma_2^b} \tag{9}$$

where $0 \leq \gamma_2^b < 1$ and γ_{1t}^b control for the curvature and the marginal effect on emissions to brown energy production, respectively. A lower value of γ_{1t}^b can be interpreted as an improvement in the efficiency of emissions by brown energy producers, which contributes to the decarbonization of the economy. We assume the presence of an exogenous rate of technological progress, denoted as $g_{\gamma_1^b}$, which influences the dynamics of emission efficiency. This relationship is described by the following equation:

$$\gamma_{1t}^b = \gamma_{10}^b \left(1 - g_{\gamma_1^b}\right)^t \tag{10}$$

where γ_{10}^b is the calibrated value of this variable corresponding to the benchmark period.

By considering the more realistic case of making emissions dependent on a particular type of energy production, we curb the close relationship between carbon generation and aggregate output and allow emissions reductions to be achieved not only by reducing output but also by changing inputs.

Firms pay a tax τ_t^e per unit of emissions. The existence of a cost for emitting carbon into the atmosphere creates an incentive to abate emissions. The variable μ_t^b is the fraction of emissions abated by the brown energy producers. We assume that the abatement costs of brown energy producers, z^b, are proportional to energy production,

$$z_t^b = \theta_1^b \left(\mu_t^b\right)^{\theta_2^b} v_t^b \tag{11}$$

The optimization problem faced by the green energy production firms sector can be written as follows:

$$\max_{k_{t-1}^g} \quad P_t^{vg} v_t^g - P_t r_t^g k_{t-1}^g \qquad s.t$$

$$v_t^g = \varsigma_t^g \left(k_{t-1}^g\right)^{\alpha^g}$$

Similarly, brown energy producers maximize profits subject to the production and emissions technologies.

$$\max_{k^b_{t-1}, m^b_t, \mu^b_t} \quad P^{v^b}_t v^b_t - P_t r^b_t k^b_{t-1} - (1+\tau^m_t) P^{*m^b}_t m^b_t - P_t \tau^e_t e^b_t - P_t \theta^b_1 \left(\mu^b_t\right)^{\theta^b_2} v^b_t \qquad s.t$$

$$v^b_t = \left(k^b_{t-1}\right)^{\alpha^b} \left(m^b_t\right)^{(1-\alpha^b)}$$

$$e^b_t = \left(1-\mu^b_t\right) \gamma^b_{1t} \left(v^b_t\right)^{1-\gamma^b_2}$$

where $P^{v^l}_t$ is the price of type-l energy, $P^{*m^b}_t$ is the exogenous price of the imported energy commodity, and τ^m_t is an exogenous price shifter, essentially a change in the international market price of the commodity, or a tariff/subsidy applied to this commodity by the government.

From the above problem optimal decisions about energy production, and emissions are derived. Emissions abatement is guided by the following expression

$$\mu^b_t = \left[\frac{\tau^e_t \gamma^b_{1t}}{\theta^b_1 \theta^b_2} \left(v^b_t\right)^{-\gamma^b_2} \right]^{\frac{1}{\theta^b_2 - 1}} \tag{12}$$

Without internalizing some of the environmental costs of emissions, there are no incentives to reduce emissions, resulting in zero abatements when taxes on emissions (or the price of carbon emissions permits) are zero.

Profits in both sectors are given by

$$\Gamma^{v^g}_t = (1-\alpha^g) p^{v^g}_t v^g_t \tag{13}$$

$$\Gamma^{v^b}_t = -\tau^e_t \gamma^b_2 e^b_t \tag{14}$$

2..3 Energy suppliers

Energy suppliers package a mix of green and brown energy that they sell to intermediate goods producers at a price of $P^{v^y}_t$. The packaging technology is given by,

$$v^y_t = A^x_t \left[\theta^g \left(v^g_t\right)^{\frac{\sigma^x - 1}{\sigma^x}} + (1-\theta^g) \left(v^b_t\right)^{\frac{\sigma^x - 1}{\sigma^x}} \right]^{\frac{\sigma^x}{\sigma^x - 1}} \tag{15}$$

where v_t^y is the total energy supplied, and σ^x is the elasticity of substitution between green and brown energy.

Using equations (6) and (7), the supplied energy package for intermediate production can be written in terms of capital as,

$$v_t^y = A_t^x \left[\theta^g \left(\varsigma_t^g f^g(k_t^g) \right)^{\frac{\sigma^x - 1}{\sigma^x}} + (1 - \theta^g) \left(f^b(k_t^b, m_t^b) \right)^{\frac{\sigma^x - 1}{\sigma^x}} \right]^{\frac{\sigma^x}{\sigma^x - 1}} \tag{16}$$

Energy packers solve the following optimization problem

$$\min_{v_t^g, v_t^b} \quad p_t^{v^g} v_t^g + p_t^{v^b} v_t^b$$

s.t.

$$v_t^y = A_t^x \left[\theta^g \left(v_t^g \right)^{\frac{\sigma^x - 1}{\sigma^x}} + (1 - \theta^g) \left(v_t^b \right)^{\frac{\sigma^x - 1}{\sigma^x}} \right]^{\frac{\sigma^x}{\sigma^x - 1}} \tag{17}$$

Under perfect competition, profits in this sector are zero, so the unit cost derived from this problem, $c_t^{v^y}(p_t^{v^g}, p_t^{v^b})$, is equal to $p_t^{v^y}$, the price of one unit of energy mix

$$p_t^{v^y} = \left[(\theta^g)^{\sigma^x} \left(p_t^{v^g} \right)^{1 - \sigma^x} + (1 - \theta^g)^{\sigma^x} \left(p_t^{v^b} \right)^{1 - \sigma^x} \right]^{\frac{1}{1 - \sigma^x}} \tag{18}$$

2..3.1 Intermediate non-energy producers

A large number of firms operate under monopolistic competition to produce a differentiated good ($y_t(i)$) using capital ($k_t^y(i)$), labor ($h_t(i)$), and energy ($v_t^y(i)$),

$$y_t(i) = A_t^y(i) k_{t-1}^y(i)^{\alpha^y} h_t(i)^{\beta^y} v_t^y(i)^{1 - \alpha^y - \beta^y} \tag{19}$$

where $A_t^y(i)$ is total factor productivity at the intermediate good firm level. [1]

Firms face a downward-sloping demand curve

$$y_t(i) = \left(\frac{P_t(i)}{P_t} \right)^{-\sigma^r} y_t \tag{20}$$

where y_t is aggregate production. They pay a quadratic adjustment cost à la Rotemberg (1982) for changing prices.

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[1] Fabra, Lacuesta and Souza (2022) use a similar function for aggregate production with a single energy input.

$$AC_t(i) = \frac{\kappa_p}{2}\left(\frac{P_t(i)}{P_{t-1}(i)} - \bar{\pi}\right)^2 P_t y_t \tag{21}$$

The optimization problem for intermediate firms can be written as,

$$\max_{P_t(i),h_t(i),k^y_{t-1}(i),v^y_t(i)} \mathbb{E}_0\{\sum_{t=0}^{\infty}\beta^t\frac{\lambda_t}{\lambda_0}[\left(\frac{P_t(i)}{P_t}\right)y_t(i) - w_t h_t(i) - r^y_t k^y_{t-1}(i)$$
$$-p^{v^y}_t v^y_t(i) - \frac{\kappa_p}{2}\left(\frac{P_t(i)}{P_{t-1}(i)} - \bar{\pi}\right)^2 y_t]\} \qquad s.t$$

$$y_t(i) = \left(\frac{P_t(i)}{P_t}\right)^{-\sigma^r} y_t$$

$$y_t(i) = A^y_t(i)k^y_t(i)^{\alpha^y}h_t(i)^{\beta^y}v^y_t(i)^{1-\alpha^y-\beta^y}$$

We assume a symmetric equilibrium so that firms choose the same price, inputs, and output. Aggregate profits for the intermediate goods producers are:

$$\Gamma^y_t = y_t\left(1 - mc_t - \frac{\kappa_p}{2}(\pi_t - \bar{\pi})^2\right) \tag{22}$$

2..3.2 Final-good firms

The representative final-good firm produces an aggregate good y_t from different varieties using a CES aggregator,

$$y_t = \left[\int_a^b y_t(i)^{\frac{\sigma^r-1}{\sigma^r}} di\right]^{\frac{\sigma^r}{\sigma^r-1}} \tag{23}$$

where $y_t(i)$ represents intermediate goods produced under monopolistic competition.

The optimization problem is,

$$\max_{y_t(i)} P_t y_t - \int_a^b P_t(i) y_t(i) di \tag{24}$$

and profits at this level of production are zero.

2..4 Environmental and economic damage

Emissions feed the atmospheric carbon stock, x_t,

$$x_t = \eta_t x_{t-1} + e_t + e_t^{row} \tag{25}$$

where e_t are aggregate domestic emissions (brown energy production emissions) and e_t^{row} are the (exogenous) emissions of the rest of the world. x_t represents kilotonnes (kt) of atmospheric carbon (GtC) and $1 - \eta_t$ represents the rate of carbon absorption.

The function representing the impact of the atmospheric carbon stock on total factor productivity is as follows: [2]

$$A_t^y = [1 - d_0 x_t^{d_1}]\widetilde{A}_t^y \tag{26}$$

The economic cost of CO2 accumulation is convex, as in Dietz and Stern (2015). Variable $\widetilde{A}_t^y$ is the zero-carbon TFP that evolves exogenously due to exogenous technological progress, represented by $g_{\widetilde{A}}$. The evolution of $\widetilde{A}_t^y$ is described by the equation:

$$\widetilde{A}_t^y = \widetilde{A}_0^y \left(1 + g_{\widetilde{A}}\right)^t \tag{27}$$

Here, $\widetilde{A}_0^y$ represents the initial calibrated value of the zero-carbon TFP for the benchmark period.

2..5 The government and the central bank

The central bank follows a standard Taylor's rule,

$$\frac{r_t}{r} = \left(\frac{r_{t-1}}{r}\right)^{\rho_r} \left[\left(\frac{\pi_t}{\pi}\right)^{\phi_\pi} \left(\frac{y_t}{y}\right)^{\phi_y}\right] \tag{28}$$

where r_t is the policy rate, and π and y correspond to the steady state inflation rate and output.

The government finances public spending (g_t) and green investment subsidies (τ_t^{ig}) by levying lump sum taxes on households (τ_t^h), tariffs on imported energy commodity ($\tau_t^m p_t^{*m^b} m_t^b$), and emission taxes on energy-producing firms (τ_t^e). So, the budget constrain can be written as,

$$g_t + \tau_t^{ig} i_t^g = \tau_t^h + \tau_t^m p_t^{*m^b} m_t^b + \tau_t^e e_t \tag{29}$$

Factors contributing to reducing carbon emissions can be divided, as in Burda and

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[2] While the economy's emissions contribute only to a fraction of global emissions, implying a relatively minor impact on the carbon stock and economic damage from environmental measures, we include this damage function for comprehensive analysis. It also enables us to make comparisons later on regarding emissions reduction scenarios in a coordinated global context, where the rest of the world achieves similar environmental outcomes as our benchmark economy.

Zessner-Spitzenberg (2022), into two blocks. The first block has to do directly with technology improvements in the green energy production sector (changes in v_t^g)) or the brown technology of carbon emissions (changes in γ_{1t}^b). The second block implies different instruments of fiscal policy, such as green energy investment subsidies, a tariff on fuel commodities, or a tax on carbon emissions.

2..6 Market clearing

Using the households' and government budget constraints, the definition of profits at each production level, and some first-order conditions, and assuming a balanced government budget every period ($b_t = 0$), we can derive the expression for aggregate output as follows:

$$y_t = c_t + i_t^y + i_t^g + i_t^b + g_t + p_t^{*m^b} m_t^b + \theta_1^b \left(\mu_t^b\right)^{\theta_2^b} v_t^b + \frac{\kappa_p}{2} \left(\pi_t - \bar{\pi}\right)^2 y_t \tag{30}$$

3. Calibration

We calibrate the model annually to replicate some energy and environmental ratios of the Spanish economy in 2010 which is taken as an example in our simulations. In our calibration, we establish a clear distinction between green and brown energy. Specifically, green energy encompasses all forms of energy that do not produce carbon emissions, such as hydraulic, nuclear, and renewable energy. The remaining energy sources, including coal-fired energy, combined cycle energy, and cogeneration, are considered dirty or brown. Emissions and air pollution are measured in kilotonnes of carbon, while energy is measured in kilotonnes of oil equivalent. We normalize aggregate GDP to 1 million euros, which allows us to interpret most variables in terms of million euros of production.

Next, we provide a comprehensive overview of the strategy employed to calibrate the parameters in the model. Detailed information on the values used in the model and the pertinent macroeconomic ratios that align with the static solution of the model can be found in Appendix B.

3..1 Parameters from the literature

We adopt a value for the elasticity of substitution between green and brown energy, $\sigma^x = 3.94$, based on Table 2 in Stockl and Zerrahn (2020).[3] This elasticity is higher than those

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[3] If we consider that the same production services can be obtained from both green and brown energy inputs, we can expect the elasticity of substitution to be very high. However, there are several factors that prevent this elasticity of substitution from being infinite, as discussed by Pageorgiou et al. (2017). Firstly,

estimated by Pageorgiou et al. (2017), which range between 2 and 3.

For the convex capital adjustment cost function, $\kappa_I^y = 15$, we adopt the parameter from Annicchiarico and di Dio (2015). Given the characteristics of energy capital, we assume that the adjustment costs for the capital used in energy production are 1/3 higher than the average adjustment cost for the capital used in the production of goods, leading to $\kappa_I^g = \kappa_I^b = 20$. We derive our choice for the value representing energy expenditure as a share of GDP from the Annual Energy Review of the US Energy Information Administration (2022). Based on this report, we set $1 - \alpha^y - \beta^y = 0.07$. [4]

3..2 Parameters from empirical evidence and model equations

We determine the value of α^b based on two shares. First, we consider the share of total energy used for energy production, which was reported as 28% according to Eurostat (2022).[5] Secondly, according to Red Eléctrica de España (2019),[6] brown energy accounted for 47% of the total installed energy in 2010. We aim for $1 - \alpha^b$ to be close to the ratio between these two shares. Consequently, we set $\alpha^b = 0.5$.

We assume that the output-to-capital elasticity in green energy production is the same as in dirty energy production, leading us to set $\alpha^g = 0.5$. To determine the depreciation rate of capital used in the production of goods ($\delta_y = 4.43\%$), we refer to the annual accounting depreciation rate applicable in Spain for various types of capital, such as transport, machinery, and non-residential buildings, as documented by Tax Partners (2015). We calculate the weighted average of depreciation rates by considering the proportions of different capital types, relying on Prados de la Escosura (2020) for the required weights. Using the static version of the model equations, we calibrate two additional depreciation rates. This calibration allows us to simultaneously align the energy intensity per unit of GDP and the ratio between the prices of green and brown energy in 2010. As a result, we obtain calibrated values of $\delta_b = 3.27\%$ and $\delta_g = 4.14\%$. The findings regarding depreciation rates indicate that energy infrastructure generally has a longer useful life compared to standard capital used directly in the production of goods, with capital for dirty energy production having the longest lifespan.

the issue of storage remains a challenge for renewable energy sources, leading to a mismatch between supply and demand during peak periods. Secondly, as renewable energy expands, the marginal productivity decreases, as new installations may be located in less optimal areas for energy generation. Lastly, certain industries still rely on fossil fuels as an energy source, such as cement, steel, ceramics, and transportation.

[4] In the Energy Overview category, specifically in Section 1.5, the energy expenditure as a share of GDP was reported as 8.1%. Our choice to reduce this percentage for Spain is based on a significantly lower intensity of energy use in Spain relative to the U.S. (9.0% in Spain and 15.0% in the U.S., according to OECD, 2015)

[5] Eurostat: Energy Statistics - An Overview

[6] El Sistema Eléctrico Español. Informe 2019

The time discount rate, β, is calibrated to ensure that the static version of the model reproduces an annual real interest rate of 4%. This calibration aligns with the recommendation by Nordhaus (2007) to replicate realistic rates of capital return.

To match the ratio of installed green energy to brown energy, based on data from Red Eléctrica de España (2019), we calibrate the distribution parameter in the energy CES composite of goods as $\theta^g = 0.47$. We consider a non-policy benchmark scenario for the year 2010, which implies setting $\tau = \tau^{ig}_{2010} = \tau^m_{2010} = 0$ (no taxes or subsidies).[7] We calibrate $\widetilde{A}^y_{2010} = 0.8368$ to ensure that the static model solution is consistent with the capital-to-output ratio for goods production.

Given the long-run nature of all the simulations, we set the price stickiness parameter, κ_p, to virtually 0, enabling full price flexibility. However, the model retains the ability to conduct short-run analysis by modifying this assumption and allowing the Taylor rule to be fully operational in a world of price rigidity.

3..3 Utility function

We set the risk aversion for the utility of consumption, σ, as $\frac{1}{0.7}$, consistent with the estimations of the intertemporal elasticity of substitution for consumption in the Spanish economy from Cutanda, Labeaga, and Sanchis-Llopis (2020). The risk aversion for the utility of leisure, denoted as θ, is established at $\frac{1}{0.4}$, derived from the average of intertemporal elasticities of substitution for leisure in Spain, as documented in Cutanda and Sanchis Llopis (2022). The parameter θ, which determines the weight of leisure relative to consumption in the utility function, is selected to achieve a target of one-third for working hours in 2010, considering that the total time is normalized to 1.

3..4 Atmospheric carbon accumulation

Atmospheric carbon is driven by total domestic emissions e and exogenous emissions from the rest of the world e^{row},

$$x_t = \eta x_{t-1} + e_t + e^{row} \tag{31}$$

Here, $1 - \eta_t$ represents the yearly carbon decay rate, which can be calibrated based on the half-life of atmospheric carbon dioxide. The literature provides varying estimates for this parameter, making it challenging to determine an exact value. Moore and Braswell (1994) estimate the half-life of atmospheric CO2 to range between 19 and 92

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[7] Environmental taxes still nowadays represent only a modest part of total government revenues and affects a negligible part of emissions (see Delgado-Téllez *et al.*, 2022).

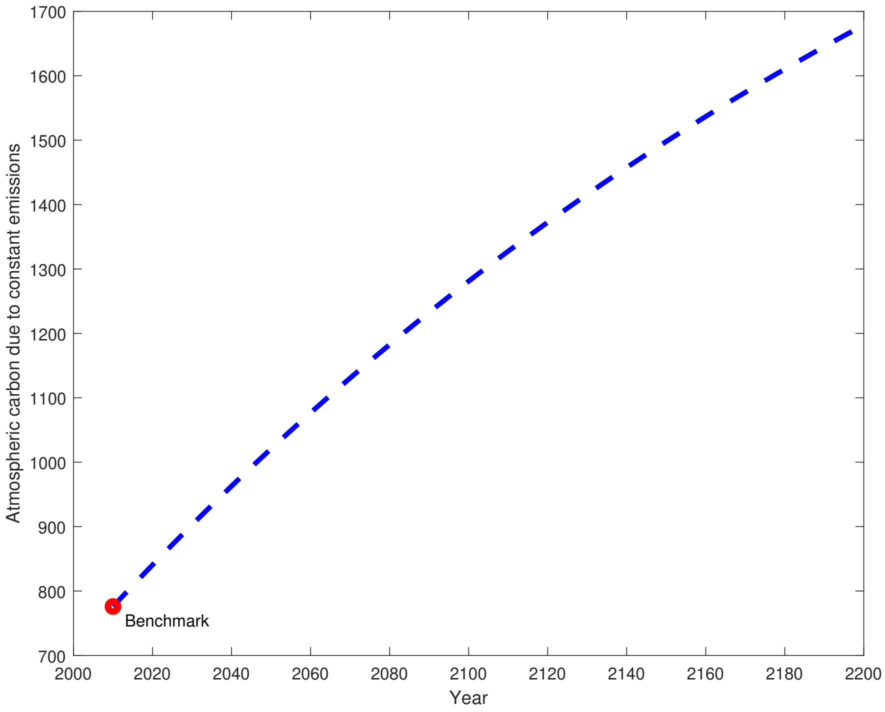

Figure 1: *Carbon stock trajectory for constant global emissions at the 2010 global level*

years under different assumptions. Heutel (2012) assumes a half-life of 83 years, corresponding to a quarterly parameter η of 0.9979. Other evidence, supported by the NASA indicates that a fraction of fossil carbon dioxide can persist in the atmosphere for hundreds to thousands of years (Archer and Brokvin, 2008; and Archer *et al.*, 2009).

Our approach assumes that terrestrial ecosystems absorbed around 30% of global emissions in the long run, a figure consistent with observations over the past 50 years (Brienen et al., 2020). Hence, we set $\eta = 1 - \frac{0.3e_{2010}}{x_{2010}}$.

In 2010, yearly emissions in Spain amounted to 79,381 kt of carbon (or 0.0741 kt per million euros of production) [8]. This accounted for 0.79% of world emissions. Employing Equation (31), we project the trajectory of carbon stock assuming emissions persist at the 2010 global level and without economic intervention, depicted in Figure 1. The calculated value of η at 0.9964 implies an average atmospheric carbon half-life of approximately 190 years $(-log(2)/log(\eta))$.

[8] Data from CO2 emissions in IEA-EDGAR CO2 (2022) transformed to carbon emissions.

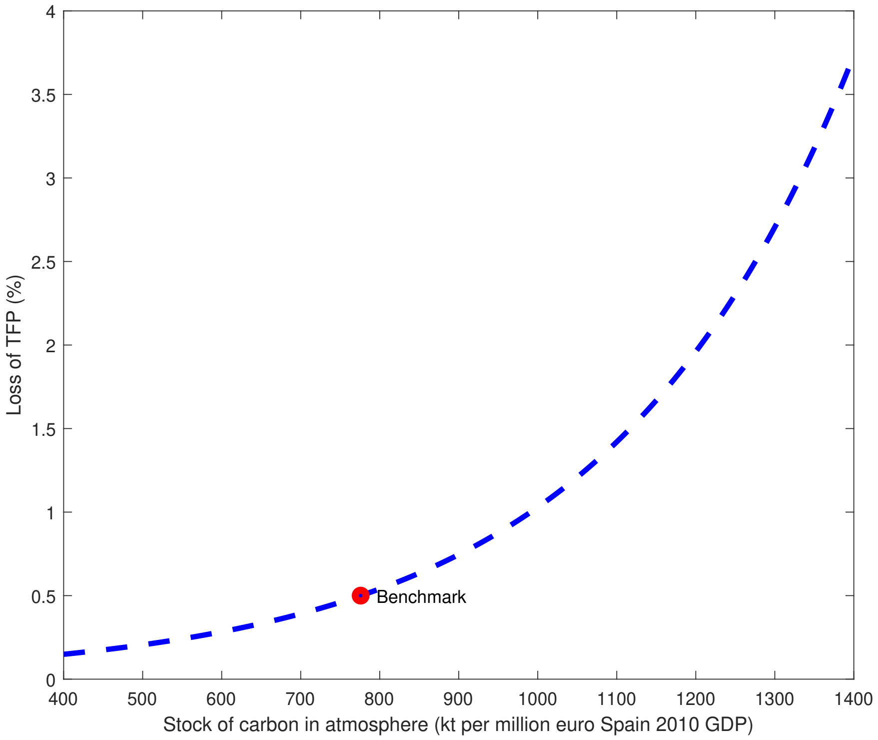

Figure 2: *Economic cost (% of TFP) as a function of atmospheric carbon*

3..5 The damage function

We adjust an exponential damage function, $d(x_t) = d_0 d_1^{x_t}$, to approximate the *laissez-faire* damage trajectory as depicted in Figure 6 by Golosov *et al* (2014b).[9] The calibrated parameters result in $d_0 = 4.1064e - 04$ and $d_1 = 1.0032$.

Figure 2 represents how this function varies with the stock of atmospheric carbon and specifically marks the values corresponding to the 2010 benchmark year. Atmospheric carbon stock of approximately 776 kt per million GDP corresponds to a loss of TFP of 0.5%. Increasing atmospheric carbon mass by 50% leads to a TFP loss of 1.7%.

[9] Some researchers prefer utilizing a quadratic damage function. For instance, Heutel (2012) calibrates coefficients within a quadratic damage function $d(x) = d_0 + d_1 x + d_2 x^2$ based on the DICE-2007 model by Nordhaus (2008). Our setting implies slightly higher damage for a likely range of values for x_t.

3..6 Emissions

According to Heutel (2012) and Annicchiarico and Di Dio (2015), aggregate emissions are an increasing and (possibly) concave function of GDP:

$$e_t^b = (1 - \mu_t^b)\gamma_1 y_t^{1-\gamma_2}$$

Here, μ_t^b represents the fraction of emissions optimally abated by the economy, which is zero in the benchmark scenario of no carbon taxation. In our model, we link aggregate emissions to brown energy, resulting in the equation:

$$e_t^b = \left(1 - \mu_t^b\right)\gamma_1^b \left(v_t^b\right)^{1-\gamma_2^b}$$

To ensure consistency with the observed emissions, zero abatement, and brown energy production in 2010, γ_1^b should satisfy the equation:

$$\gamma_1^b = \frac{e_{2010}^b}{\left(v_{2010}^b\right)^{1-\gamma_2^b}} \tag{32}$$

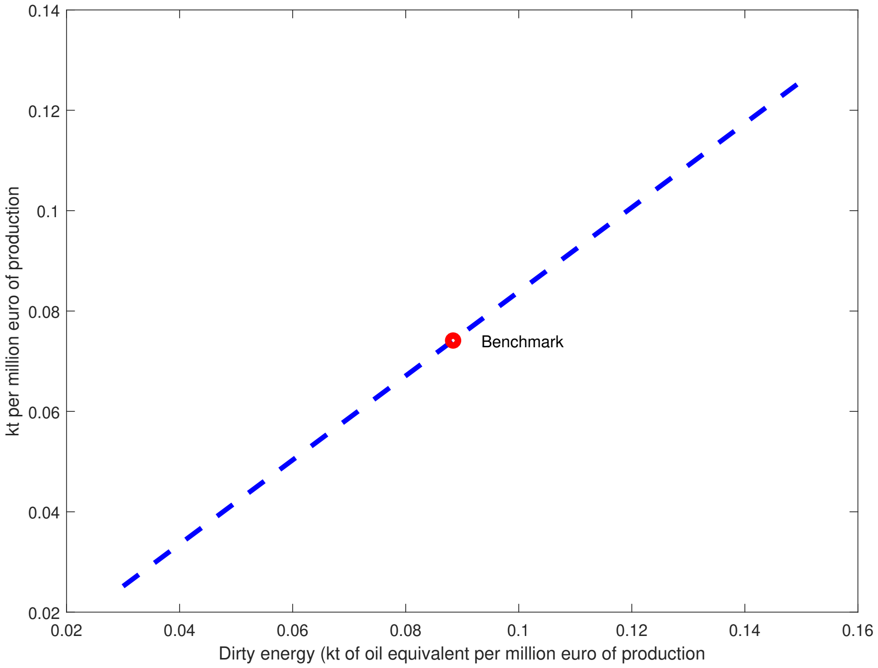

Figure 3: *Emissions as a function of dirty energy production*

Heutel (2012) takes $\gamma_1^b = 1$ and $1 - \gamma_2^b = 0.696$. However, Annicchiarico and Di Dio (2015) assume that $\gamma_2^b = 0$. We also adopt $\gamma_2^b = 0$, and obtain $\gamma_1^b = 0.8386$ from equation (32), because it is consistent with the empirical evidence for the Spanish economy from 1985 to 2005 when the contribution of renewable energy to the production of primary energy was below 5%. During this period, the ratio of CO2 emissions to GDP was relatively constant and the contribution of oil, gas, and coal was also steady, around 80% (the remaining 15% obtained from nuclear and hydroelectric sources), suggesting that the elasticity of emissions to dirty energy production was close to 1.0,

Sen and Vollebergh (2018) estimate that an increase of 1 € in energy taxes imposed on each tonne of CO2 leads to a long-run reduction in emissions from energy consumption by 0.73%. However, Metcalf (2019) obtains a larger 10-year elasticity of emissions to carbon taxes (-1.11). We check with our model that increasing the price of the commodity used to produce brown energy by 1% would result in a long-term emission drop of 0.97%. The relationship between emissions and normalized brown energy output is illustrated in Figure 3.

3..7 Abatement costs

The ratio $z(\mu_t^b)/y_t$ represents the cost, relative to total output, of abating a fraction μ_t^b of emissions. Heutel (2012) assumes a parameter elasticity of the cost of abatement, $\theta_2^b = 2.8$, based on Nordhaus (2008). We adopt the same elasticity for our equation (11). Regarding the scale coefficient, Heutel (2012) sets $\theta_1^b = 0.05607$, indicating that eliminating emissions would cost 5.6% of GDP, but this cost is allowed to decrease over time to 3.92% within 50 years. However, Annicchiarico and Di Dio (2015) assume $\theta_1^b = 0.185$. To reconcile these differences, we choose θ_1^b such that it results in a cost of 12% of GDP for $\mu_t^b = 1$, which is the average between Heutel (2012) and Annicchiarico and Di Dio (2015). This yields a value of $\theta_1^b = 1.34$ in our model because we write this cost in terms of brown energy production.

Figure 4 illustrates the relationship between the cost and the percentage of abated emissions for the baseline level of dirty energy production. Note that due to the uncertainty surrounding these and other energy and environmental parameters, we conduct a sensitivity analysis at the end of the next section, where we significantly vary their values.

4. Results

We use the model to evaluate the economic consequences of implementing various mitigation policies to meet the 2050 emission targets in Spain. First, we establish a baseline scenario for Spanish emissions between 2010 and 2050, assuming no policy intervention and maintaining constant annual carbon emissions worldwide at their 2010 levels. To achieve this, we calibrate the growth rate of specific exogenous technological variables by referencing observed changes in Spain's GDP, carbon emissions, and the proportion of green to brown energy production from 2010 to 2019.

4..1 Baseline scenario: 2010-2019

Between 2010 and 2019, Spain's real GDP increased by 10.6%, while carbon emissions decreased by 11.8% and the ratio of green energy production to brown energy increased by 14.5%. We attribute these changes to different types of technological progress, specifically, technological progress that increases total factor productivity ($g_{\widetilde{A}}$), technological progress that reduces emissions per unit of energy production ($g_{\gamma_1^b}$), and technological progress biased towards green energy production (g_{ς^g}). It should be noted that this approach provides an upper-bound estimate of the potential impact of technological progress on decarbonization during the studied period. This is because we do not ac-

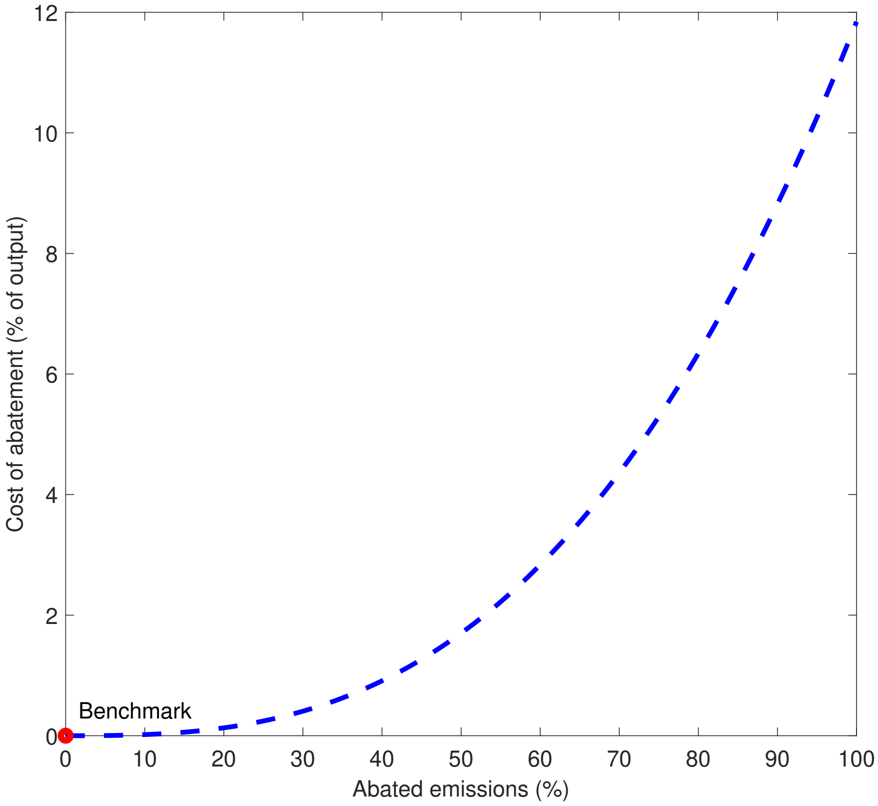

Figure 4: *Abatement costs as a function of the abatement share of emissions*

count for other regulatory or fiscal mitigation policies implemented between 2010 and 2019.[10]

To calibrate the composition of the three sources of technical progress that best account for these observed changes, we introduce unanticipated series for $\widetilde{A}^y_t$, ς^g_t, and γ^b_{1t} over a 10-period span from 2010 to 2019. Each series has a different constant growth rate (technology progress), and these growth rates are calibrated such that when the three unanticipated series, starting from their initial calibrated values $\widetilde{A}^y_0$, ς^g_0, and γ^b_{10} are included together in the model, the dynamic solution matches the observed global rates of GDP growth, carbon emissions reduction, and the relative increase in green energy production between 2010 and 2019.

The results are presented in Table 1. The observed increase in GDP, the decrease in

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[10] See footnote 7.

	Rate of Growth of Different Types of Technological Progress
TFP growth ($g_{\tilde{A}}$)	1.21
Green bias tech progress (g_{ς^g})	1.79
Emissions efficiency ($g_{\gamma_1^b}$)	1.68
	Individual Contribution to Emissions
TFP growth ($g_{\tilde{A}}$)	0.69
Green bias tech progress (g_{ς^g})	-0.39
Emissions efficiency ($g_{\gamma_1^b}$)	-1.68
	Matched Annual Growth Rates
GDP growth	1.14
Carbon emissions reduction	-1.39
Green over brown energy	1.51

Table 1: *Technology growth, individual contribution to emissions reduction, and matched growth rates (all in annual %). Source: National Institute of Statistics (Spain), Crippa et al (2022), IEA-EDGAR (2022) and our own analysis.*

emissions, and the increase in the ratio of green to brown energy production during the period are consistent with an annual growth rate of 1.21% for TFP, 1.79% for green energy bias technology, and 1.68% for emissions efficiency. Notably, the technological progress that increases the efficiency of emissions makes the largest individual contribution to the decline in emissions. However, technological progress that increases TFP increases emissions at a rate of 0.69% per year.

Figure 5 provides an overview of how the model captures the decline in emissions when considering the three types of technological progress. Taking into account only the evolution of the TFP would lead to an increase in carbon emissions. This highlights the relevance of green technology and emissions efficiency in the process of decarbonization.

4..2 Baseline scenario: 2019-2200

We utilize the calibrated growth rates of technological progress from Table 1 as annual inputs for simulating the model again. This enables us to project the dynamic trajectory of a vector of endogenous variables from 2019 to 2200, referred to as the *baseline path*, $\mathbf{x}_\mathbf{t}^\mathbf{b}$.

Figure 6a visually depicts the emission trajectory from 2019 to 2050 under the baseline scenario. It also presents two alternative scenarios considering varied paths for technological progress. In the optimistic scenario, we enhance the growth rates of exogenous green-biased technological progress and emissions efficiency by one-third, while keeping the total factor productivity (TFP) growth rate unchanged. Conversely, in the pessimistic scenario, we reduce these growth rates by one-third.

These definitions of optimistic and pessimistic scenarios significantly impact the

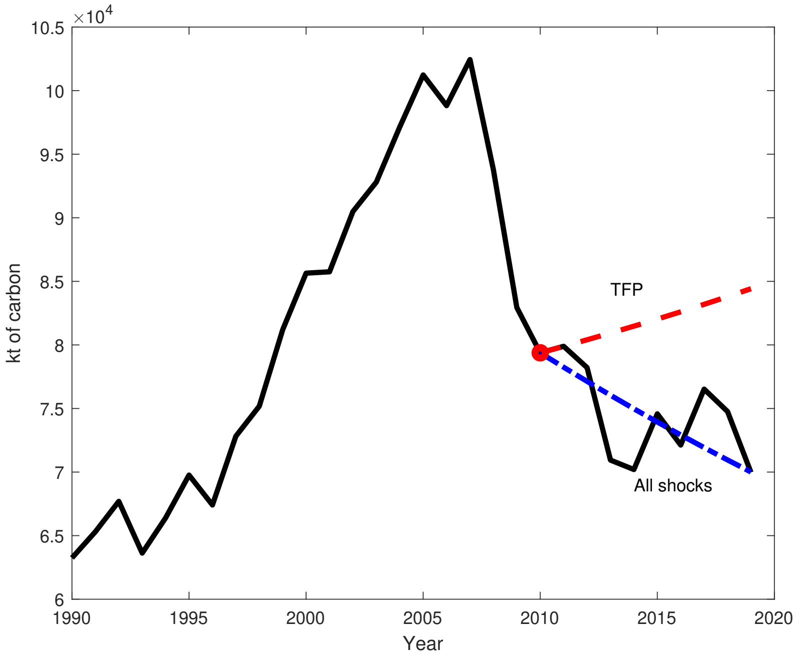

Figure 5: *Observed and projected evolution of emissions, comparing the actual trend since 2010 to a model scenario with TFP growth and decarbonization. Source: IEA-EDGAR (2022) and own analysis*

	Pesssimistic	Baseline	Optimistic
Reduction due to technology	-15.4	-32.1	-45.8
Additional effort	-54.6	-37.9	-24.2

Table 2: *Required emissions reduction in 2050 to achieve the emissions target (percentage decrease with respect to 2019)*

evolution of emissions. Furthermore, it is evident that the decline in emissions loses momentum over time.

This projection of emissions goes hand in hand with the corresponding projections of macroeconomic, energy, and environmental variables in the model. Figure 6b displays the evolution of GDP in the three scenarios considered. In the baseline scenario, GDP exhibits an average growth rate of 1.3%. However, the different technological scenarios of environmental technology have a relatively minor effect on economic performance[11]. Figure 6c highlights the progressive increase in the ratio of green to brown energy pro-

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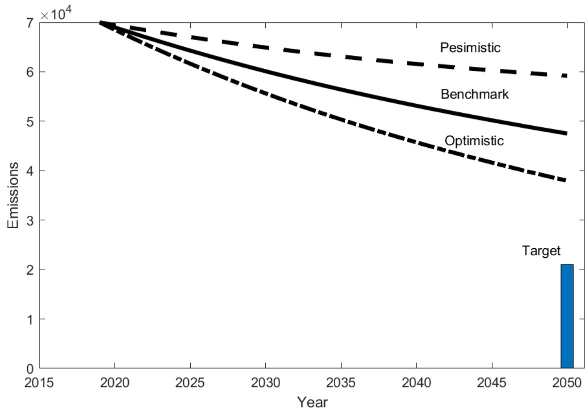
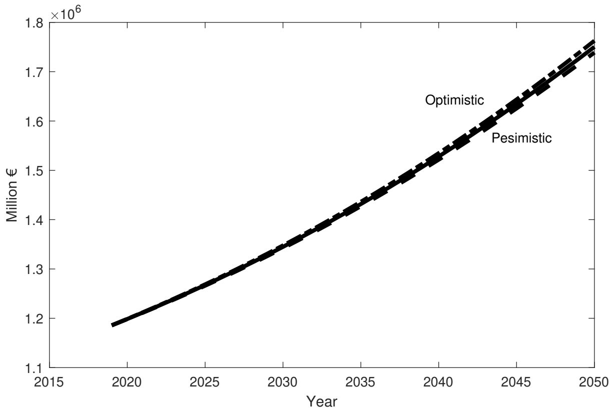
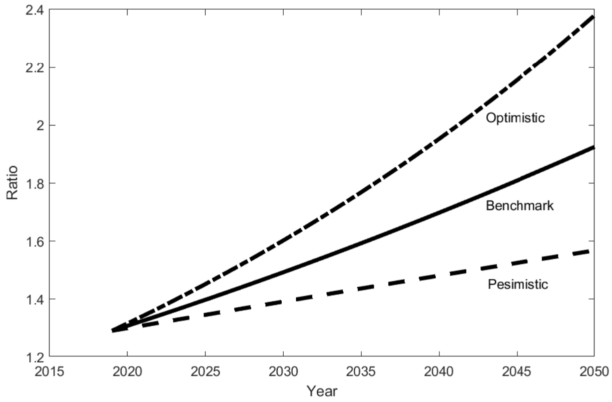
[11] Remember that our study focuses on the internal response within Spanish emissions while keeping emissions in the rest of the world constant. An examination of a coordinated strategy, where emissions in the rest of the world change proportionally to those in Spain, is detailed in Section 4..4.



(a) *Projected carbon emissions (kt)*



(b) *Projected GDP*



(c) *Projected ratio of green to brown energy*

Figure 6: *Baseline, optimistic and pessimistic scenarios 2019-2050*

duction driven by technological advancements. By 2050, this ratio is projected to increase to 1.9 under the baseline scenario.

To set the emissions target we take into account that during decades natural carbon sinks have captured about 30% of global emissions, coinciding with most of the estimates.[12] Extrapolating to Spain, we assume that reducing overall emissions by about 70% of the 2019 emissions is required to achieve the Paris Agreement's goal of net-zero greenhouse gas emissions by 2050. Taking into account the Spanish carbon emissions in 2019 under the baseline scenario, we set an emission target of 20,997 kt of carbon.

Table 2 presents the percentage reduction in emissions from 2019 to 2050 attributed solely to the expected behavior of the technology in each of the three scenarios. It also includes the additional effort required, beyond the projected 2050 values for technology, to meet the emission reduction target. In the baseline scenario, the anticipated technological advances between 2019 and 2050 are projected to achieve a reduction of 32.1% in emissions compared to 2019 levels. This represents a significant contribution to the overall target of 70% reduction. However, it leaves an additional 37.9% reduction to be achieved through mitigation policies, which will be examined in detail in the following sections. In the pessimistic scenario, a greater proportion (54.6%) of emissions reduction depends on mitigation policies, as expected technological advances in decarbonization alone are insufficient to offset emissions driven by economic growth.

4..3 Mitigation plans

The Paris Agreement calls upon each country to develop its post-2020 climate actions, referred to as Nationally Determined Contributions (NDCs). Meanwhile, within the European Union, the Fit-for-55 package proposes strategies to achieve ambitious climate objectives.

In this section, we delve into the economic implications of diverse mitigation strategies aimed at achieving a predetermined percentage reduction in emissions. To ensure a fair comparison of different plans and their economic impacts, we maintain consistency in the following manner: all examined plans, regardless of technological developments, strive for a long-term emissions reduction equal to the additional effort detailed in Table 2. In essence, we calculate the change in the policy instrument that, without considering technological changes, would result in the same steady-state alteration in emissions. It is important to note that this comparative strategy does not imply that the various policy mitigation plans scrutinized here will achieve the Net Zero Emissions (NZE) target by

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[12] See Brienen *et al.* (2020)

2050 (refer to section 4..4 for further exploration of this aspect).

We assume that all mitigation strategies considered in this analysis are initially unanticipated, meaning they were not pre-planned or expected in advance. Consequently, there is no economic response to these strategies prior to their implementation. However, once enacted, these strategies are perceived by agents as being in place indefinitely. This conceptual framework for the plans aligns with ambitious European environmental objectives that require significant policy efforts, particularly *front-loaded* ones (see Delgado-T'ellez *et al*., 2022, and Emambakhsh *et al*., 2023).[13] Once we ascertain from the comparative strategy the magnitude of the unanticipated permanent change in the exogenous variable, we incorporate the sequence of unanticipated technology shocks into the model and simulate the path of endogenous variables to obtain the *baseline plus policy scenario*, denoted as $\mathbf{x_t^{b+p}}$.

By comparing the expected evolution of relevant variables with and without the implementation of these plans, we assess both the transitional effects of the policy from 2019 to 2050 and its long-run effects by 2200. With this analysis, we aim to shed light on the potential economic implications of various mitigation strategies in bridging the emissions gap and achieving the objectives set forth in the Paris Agreement.

4..3.1 Increase in the price of imported commodity

Brown energy production relies on an imported fossil fuel commodity, represented by m_t^b (such as oil or gas). The price of this commodity, $P_t^{m^b}$, is determined in international markets and is considered exogenous in our model. Additionally, the government has the option to apply a tariff on imports of this commodity or impose a tax/subsidy on its use.

The first strategy we study is related to the price of the imported commodity used to produce energy. We assume that this price (relative to CPI) is pushed up, and the fiscal authority ensures that the relative price will stabilize at this level in the future. Depending on the international evolution of this price, the fiscal authority may need to impose taxes on the use of the commodity in some years and provide subsidies in others.

According to our findings, the price of the commodity (relative to the CPI) necessary to achieve *ex ante* the emissions target would sustainably increase by 58%. Figure 7a illustrates the resulting emissions reduction resulting from the fiscal strategy of raising and maintaining a high relative price for imported fuel commodities. Additionally, Figure 7b displays the trajectories of the ratio of brown to green energy production in the

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[13] For simulations, we utilize Dynare 5.4 and Dynare 6.0 running on Matlab R2019a.

	Commodity price	Green investment	Emissions taxes	Taxes + Subsidies
Emissions	-29.13	-13.36	-24.13	-22.21
GDP	-0.95	1.65	-0.43	0.06
Consumption	-1.05	-0.43	-0.20	-0.08
Green energy production	4.42	43.11	3.12	13.51
Brown energy production	-29.96	-15.17	-17.34	-17.02
Energy mix distribution	-12.11	14.28	-6.63	-1.20
Green energy price	7.84	-13.19	3.75	-1.89
Brown energy price	19.28	-3.22	9.71	5.75
Energy mix price	12.51	-9.66	6.28	1.20
Abatement	0.00	0.00	9.42	7.71
Year for reaching the target	2076	2072	2091	2086
% reduction target by 2050	82	79	76	77
% Green Deal target by 2030	96	92	88	89

Table 3: *Macroeconomic average effects of various mitigation plans during the period 2019-2050, expressed as average percentage deviations from accumulated baseline paths, except for abatement which is represented as the percentage reduction of accumulated emissions*

baseline and under this specific policy.

Table 3 presents the average effects during the period 2019-2050 relative to the baseline technology evolution. Consider x_t^b and x_t^{b+p} as the dynamic paths of a variable belonging to vectors $\mathbf{x_t^b}$ and $\mathbf{x_t^{b+p}}$, respectively. The average relative effect $\hat{x}_T^{av}$ is computed as follows:

$$\hat{x}_T^{av} = \frac{\sum_{t=2019}^{T} x_t^{b+p} - \sum_{t=2019}^{T} x_t^b}{\sum_{t=2019}^{T} x_t^b} \tag{33}$$

where $T = 2050$.

This strategy reduces brown energy production during the 2019-2050 period by roughly 30% on average, increases green energy production by more than 4%, and increases the cost of the energy mix by 13%. The total reduction in emissions over the period is 29%, while the cumulative loss of GDP is calculated to be about 1 percentage point. Although the 2030 intermediate objective, established under the European Green Deal, is anticipated to be significantly met[14] (96%), the accomplishment towards the 2050 Net Zero Emissions (NZE) target stands at 82%.

Figure 8 shows the percentage deviations of a selection of variables from baseline

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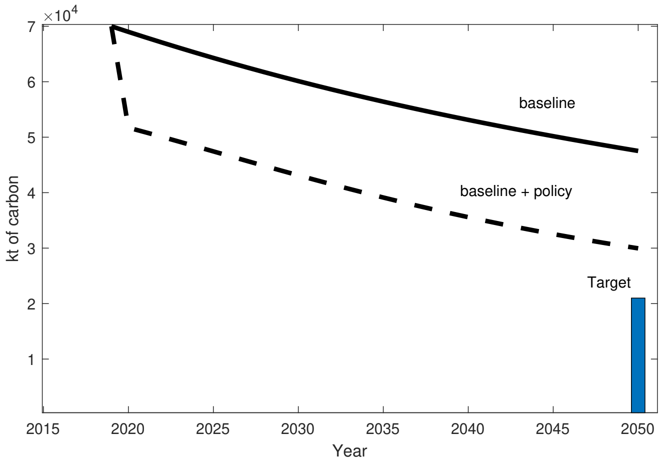
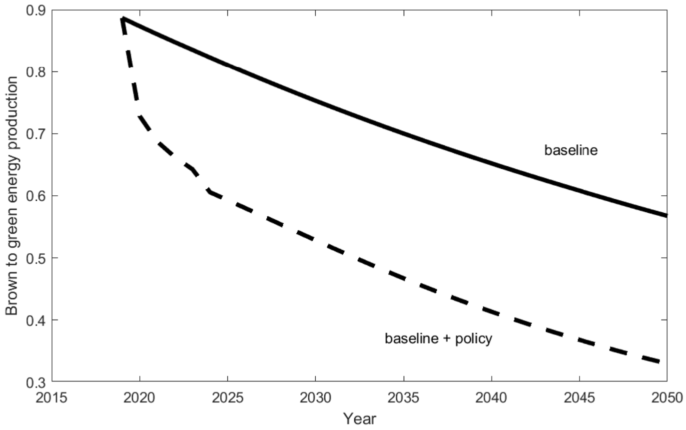
[14] Under the European Green Deal, Member States committed to reducing EU greenhouse gas emissions by 55% compared with 1990 levels by 2030.



(a) *Carbon emissions. Baseline and increase in the price of imported fuels*



(b) *Brown to green energy production. Baseline and increase in the price of imported fuels.*

Figure 7: *Increase in the price of fossil fuels*

every year from 2019 to 2100. The last subplot in the figure displays the welfare dynamics in terms of the percentage consumption required to compensate for the loss in utility. Specifically, it shows the (minus) percentage reduction in consumption that would leave households equally well-off before (baseline scenario) and after the change in the policy (baseline plus policy scenario), with a negative sign indicating a reduction in welfare. Except for a decrease in the welfare cost during the 2020s decade, the welfare cost progressively increases over time, projecting a potential loss of approximately 2.5% in terms of equivalent consumption by 2050.

This strategy entails a significant substitution of brown energy for green energy, leading to a higher price for the energy mix. However, the macroeconomic impact is relatively modest. By 2050, it is projected that GDP will be 1.1% lower compared to the baseline scenario, and consumption is expected to decrease by 1.2%.

Figure 9 illustrates the comprehensive emissions trajectory until 2200. Carbon emissions persistently decrease over time, and by 2200, the economy is projected to be emissions-free.

Table 4 compares average welfare changes relative to different technology progress scenarios for various mitigation plans in terms of equivalent consumption. More particularly, it shows

$$\bar{\omega}^{s}_{T} = \sum_{t=2019}^{T} \frac{\omega^{s+p}_{t}}{T+1-2019} - \sum_{t=2019}^{T} \frac{\omega^{s}_{t}}{T+1-2019} \tag{34}$$

The variable ω^{s+p}_{t} stands for the welfare change at period t, measured as a percentage change in equivalent consumption with respect to the initial steady state, within technology scenario s ($s = baseline, optimistic, pessimistic$) and mitigation policy p. Correspondingly, ω^{s}_{t} signifies the welfare change in terms of percentage equivalent consumption relative to the initial steady state under technology scenario s. The period T can represent either the year 2050 or the very distant year 2200.

The table's top section concerns the period from 2019 to 2050, offering insights into the transition welfare changes. The bottom part delineates the long-term projections spanning until 2200. Additionally, it details the scale of the policy instrument employed to achieve the emission target.

The results indicate a decline in welfare during the period 2019-2050 for the baseline scenario, with an average reduction of -1.6% in terms of equivalent consumption. In the long run, this reduction widens to about -14%. The long-term welfare costs reflect the implementation of the policy under the assumption of no climate actions by the rest of the world, coupled with the relatively modest influence of the Spanish economy on global

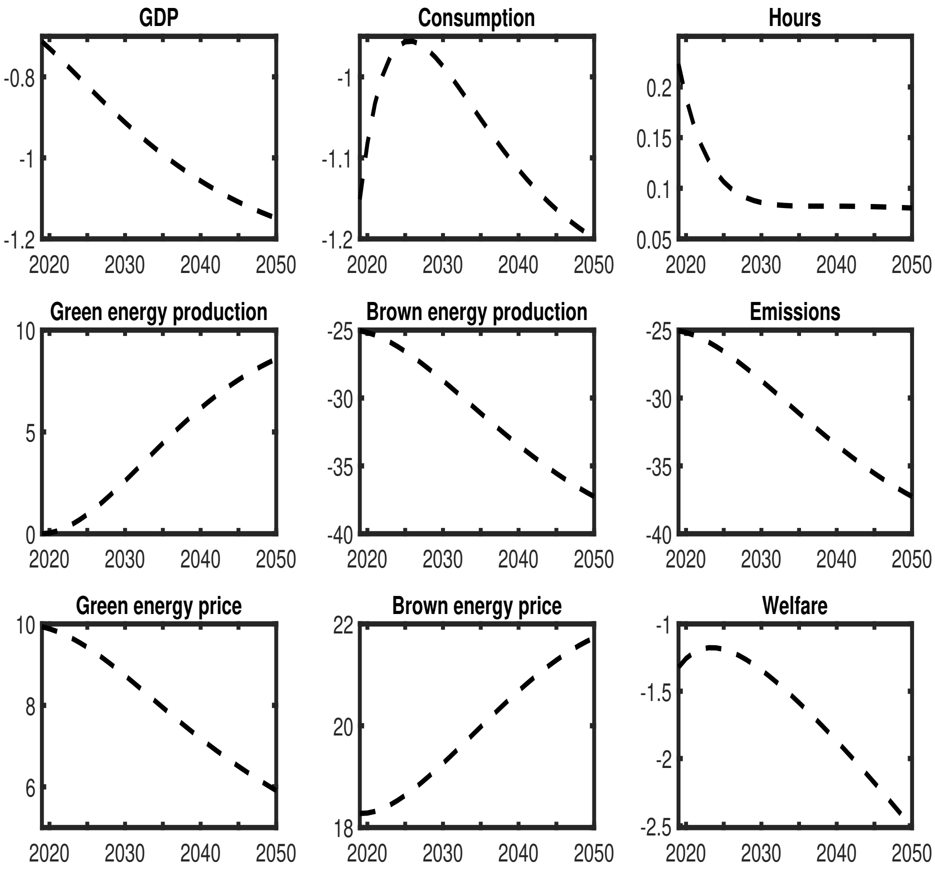


Figure 8: *Dynamic macroeconomic effects of a permanent unanticipated increase in the commodity prices (percentage deviations with respect to the baseline period)*

emissions. Therefore, implementing the policy in isolation does not sufficiently mitigate the persistent costs linked to the ongoing increase in atmospheric carbon stock.[15] In the pessimistic scenario, the projected 2019-2050 welfare loss is around -2.5%, while in the optimistic scenario, it is only about -0.9%. In the optimistic scenario, the commodity price would increase by only 31%, while in the pessimistic scenario, the increase would exceed 100%. These findings highlight the significant influence of decarbonization technologies on the overall cost of the mitigation policies.

[15] We deal with this issue in section 4..4.

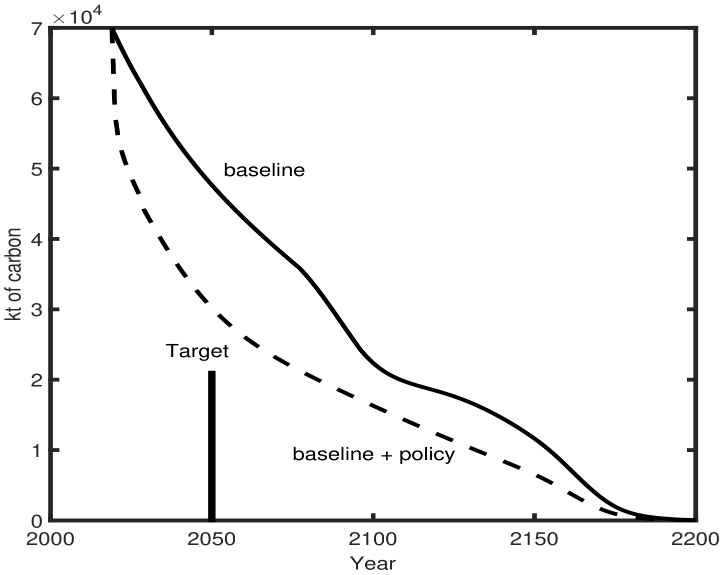


Figure 9: *Dynamic trajectory of emissions after an increase in the commodity price. Baseline and baseline + policy scenarios.*

4..3.2 Subsidies to green investment

So far, the model has operated under the assumption that the subsidy rate for green investment, denoted by the exogenous variable τ_t^{ig}, starts at zero. Now, this rate is increased once and for all to ensure the *ex ante* (without taking into account the evolution of technology) attainment in the long-term of the reduction targets outlined in Table 2, even without technological changes.

In the baseline scenario, the subsidy amounts to 62% of the investment cost, resulting in an increase of 2.6 percentage points of GDP per year in government budget costs by 2050.[16] This cost is financed by a lump-sum tax in the model economy. Figures 10a and 10b illustrate the projected paths for emissions and the relative production of brown to green production, respectively, from 2019 to 2050. By 2050, this strategy will achieve approximately 79% of the target reduction in emissions, which is reached 12 years later.

Table 3 indicates that during the 2019-2050 period, contrary to the previous mitigation strategy, a dynamic scheme of subsidies for green investment promotes GDP growth, resulting in an average 1.7% higher GDP between 2019 and 2050 compared to the baseline scenario. Green energy production augments by that year around 43% on

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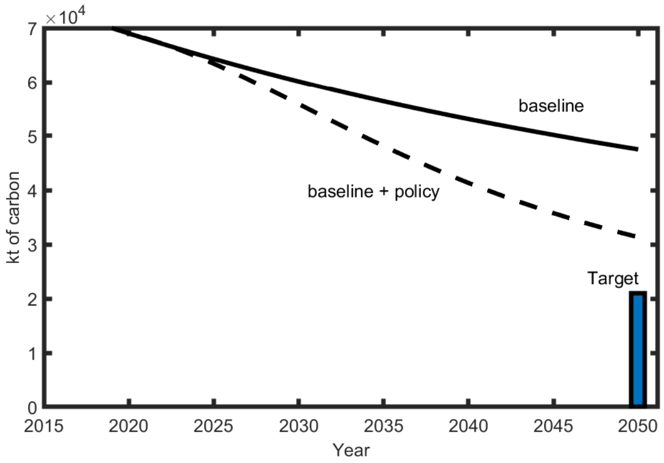
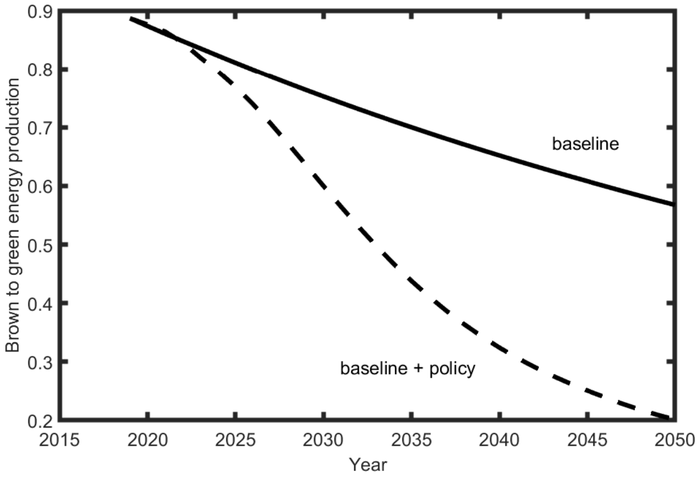
[16] These figures can be compared with the current level of climate-related public investment in Europe, which currently stands at around 1 percent of GDP (see Delgado-Téllez *et al.*, 2022)



(a) *Carbon emissions. Baseline and subsidies to green investment.*



(b) *Brown to green energy production. Baseline and subsidies to green investment.*

Figure 10: *Subsidies to green investment*

	Oil price		Green investment		Emissions taxes		Taxes + subsidies	
	Price	Welfare	Subsidy	Welfare	Tax	Welfare	Tax/Subsidy	Welfare
	(% growth)	(% growth)	(%)	(% growth)	€ per tn carbon	(% growth)	€ per tn carbon/(%)	(% growth)
2019-2050								
Baseline	58	-1.59	62	-1.11	83	-0.21	58/20	-0.08
Optimistic	31	-0.95	46	-0.08	44	-0.05	29/12	0.08
Pessimistic	107	-2.66	76	-3.87	152	-0.81	112/29	-0.73
Long run								
Baseline	58	-13.94	62	23.80	83	-7.88	58/20	1.81
Optimistic	31	-9.28	46	16.92	44	-4.99	29/12	2.00
Pessimistic	107	-24.42	76	22.62	152	-16.42	112/29	-4.72

Table 4: *Welfare effects of mitigation plans from 2019-2050 and 2019-2200, expressed as average percentage changes in equivalent consumption (negative values = loss, positive values = gain)*

average compared to the baseline, while brown energy decreases by more than 15%. The price of green energy experiences a significant drop of around 13%. This is an economy where a substantial amount of resources is allocated to green investment, driving economic growth without reducing energy intensity, but negatively impacting aggregate consumption, leisure, and welfare over some decades (see Figure 11).

The economy experiences a significant average increase in energy consumption of over 14%, driven primarily by the higher supply of non-polluting green energy. On average, there is a reduction of approximately 14% in emissions over the period. However, as we mentioned, this strategy does not lead to a reduction in energy intensity (energy use over GDP).

Despite the uptick in GDP and energy intensity, Table 4 indicates an average cumulative welfare decline of nearly 1.1% in terms of consumption during the projected baseline period. This decline primarily results from reduced consumption and increased working hours. However, in the long run, welfare notably rebounds as the favorable impacts of increased capital in the economy manifest in heightened consumption. Yet, if advancements in decarbonization technology fall below a certain threshold, the effort required in terms of consumption to subsidize green investment escalates significantly, multiplying by three the transitional welfare loss. Interestingly, although this policy, combined with the optimistic technology scenario, minimizes welfare costs between 2019 and 2050, it could result in the smallest welfare increase in the long run compared to the baseline or pessimistic scenarios. This outcome is attributed to the comparatively more restrained investment incentives resulting from the policy.

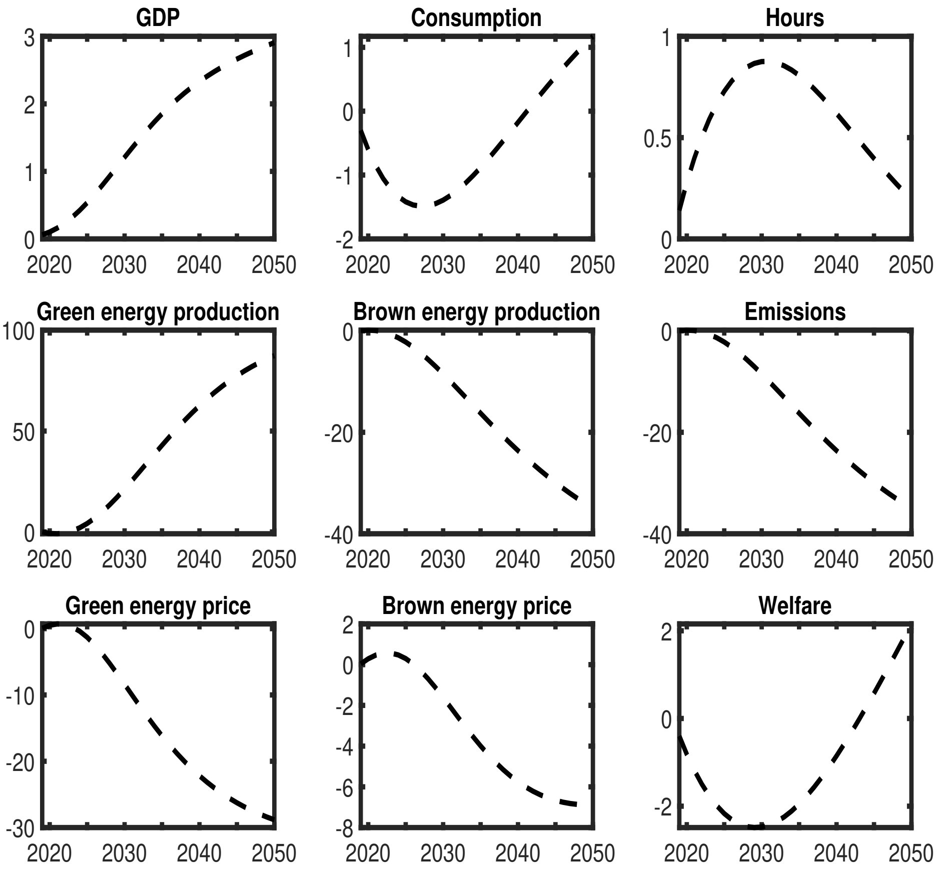


Figure 11: *Dynamic macroeconomic effects of a permanent unanticipated increase in the subsidy to green investment (percentage deviations with respect to the baseline period)*

4..3.3 Emission taxes

In this scenario, emission taxes (τ_t^e) increase permanently from 2019 onwards to achieve *ex ante* emissions target in the long run. We find that raising this tax by 83 € per tonne of carbon (at 2010 prices) would attain this goal. In the optimistic scenario, the tax would be set at 44 €, while in the pessimistic scenario, it would be 152 €. These numbers fall within a wide range of values reported in the literature. For example, Dietz and Stern (2015) suggest a range of $32-103/tCO2 [17] (at 2012 prices) in 2015, increasing to $82-260/tCO2 over the course of two decades. Delft (2010), based on a meta-analysis of vari-

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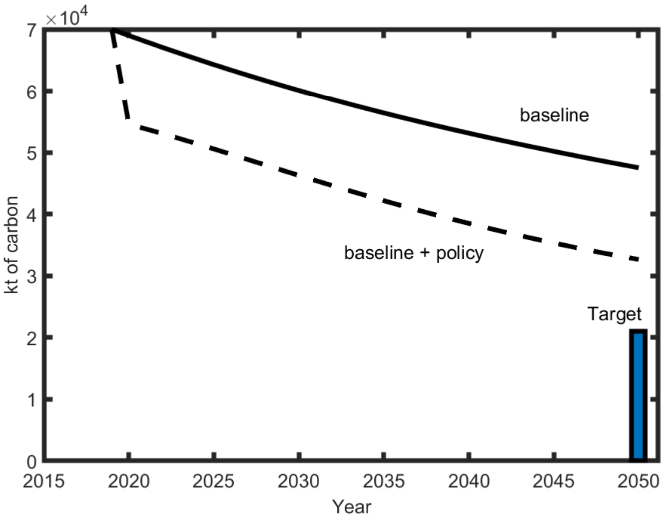
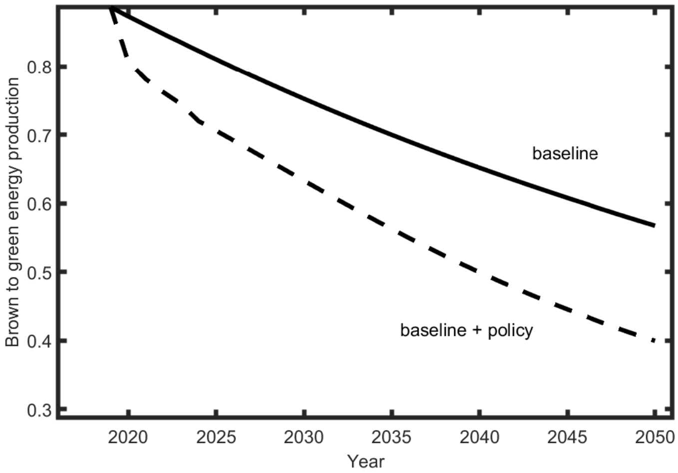
[17] To convert Euros per unit of carbon into Euros per unit of CO2, we must divide the tax by 3.67.



(a) *Carbon emissions. Baseline and emission taxes*



(b) *Brown to green energy production. Baseline and emission taxes.*

Figure 12: *Emission taxes*

ous studies, indicates that CO2 taxes could range from as low as 20 €/tCO2 to as high as 180 €/tCO2 in 2050 (at 2012 prices). Golosov *et al*. (2014), with a discount rate similar to Nordhaus, suggests an optimal tax slightly under 60 € per tonne of carbon, nearly double that of Nordhaus (see Nordhaus and Boyer, 2000). Using the same model as Golosov *et al*. (2014), but with a calibration that takes into account the world stock of carbon in the atmosphere and the world GDP both in 2019, Andrés *et al*. (2023) obtain an optimal carbon tax of $105. OECD (2021) proposes three carbon price benchmarks ranging from 30 €/tCO2 to 120 €/tCO2. According to the High-Level Commission on Carbon Pricing (2017), the price signals necessary to decarbonize electricity generation and heavy industry by 2030 would fall within the range of 30US$/tCO2 to 100US$/tCO2. Delgado-Téllez *et al*. estimate that an increase of carbon rates by €10 per tonne of CO2 is estimated to reduce emissions by 7.3% in the long term.

Figure 12 shows the path for emissions and the relative production of brown to green energy in relation to the baseline scenario, while Figure 13 represents the year-to-year percentage deviation of a set of variables with respect to the baseline. By 2050, GDP will decrease 0.7% with respect to the projected value in the baseline, dirty energy will fall by 26%, and green energy will increase by 6%. In 2050, a 76% of the target reduction is reached, and the full target is attained forty years latter.

Table 3 presents the average macroeconomic effects of the emission taxing plan from 2019 to 2050. The plan has a reduced impact on overall GDP, resulting in only a 0.4% average decrease over the period.[18] There is virtually no impact on aggregate consumption (-0.2%). Notably, firms respond to the increased taxes by investing in abatement measures that would account for a 9% reduction in accumulated emissions during the period. Figure 14 shows the dynamics of abatement in the long run. The heavily front-loaded policy initiates a rapid increase in abatement efforts, yet this response diminishes progressively over time.

The negative impacts on welfare during the period 2019-2050 are relatively small, not exceeding 1 percent point in terms of equivalent consumption, even in the pessimistic scenario, as shown in Table 4. However, in the long run, welfare experiences a decline in terms of equivalent consumption that can range from -5% in the optimistic scenario to -16% in the pessimistic scenario.

The comparison of welfare with the previous plans makes evident that emission taxes have the least detrimental impact until 2050. On the other hand, subsidies on green investment are found to be the most beneficial for long-term welfare. Figure 13 illustrates

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[18] A moderate impact of emissions taxes on GDP is also found in Delgado-Téllez *et al*., 2022.

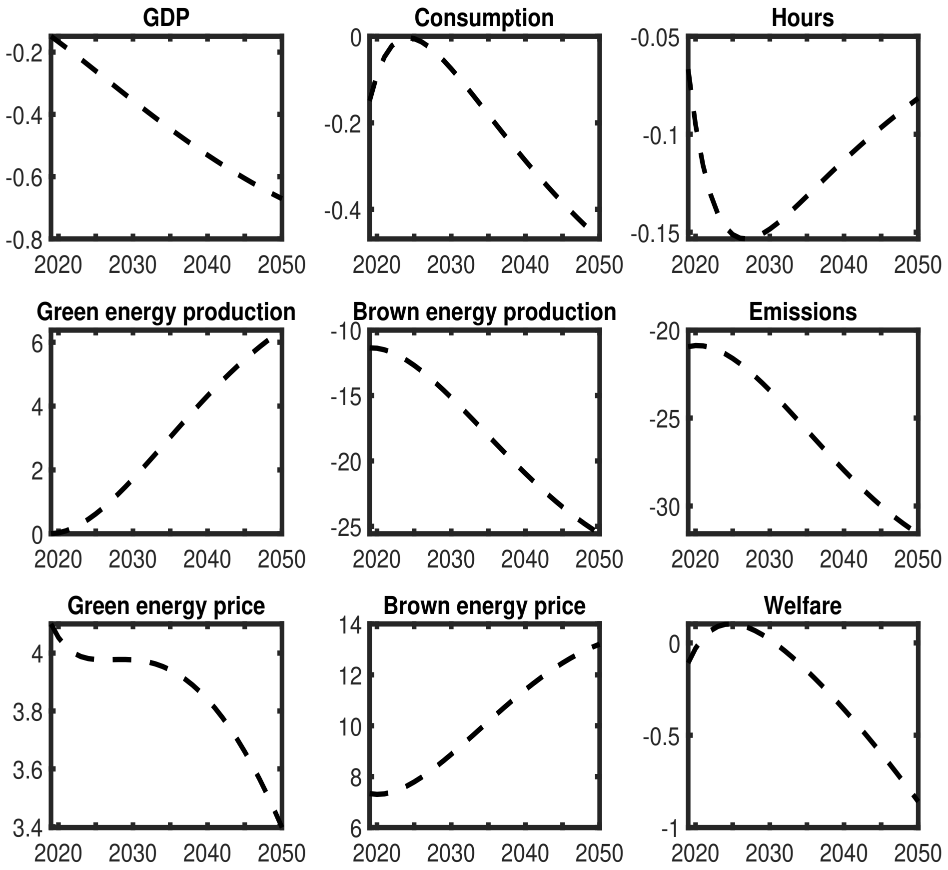


Figure 13: *Dynamic macroeconomic effects of a permanent unanticipated increase in the tax to emissions (percentage deviations with respect to the baseline period)*

that once taxes on carbon increase, the negative effects on GDP, consumption, and welfare persist over an extended period of time.

4..3.4 Emission taxes to subsidize green investment

Subsidies for green investment in the above exercise are financed through lump sum taxes. Additionally, government revenues from carbon taxes are returned to households through transfers. In this section, we examine the consequences of using carbon taxes to subsidize green investment. For this purpose, we assume that all revenues generated from taxing carbon emissions are utilized by the government to subsidize investment in green energy production.

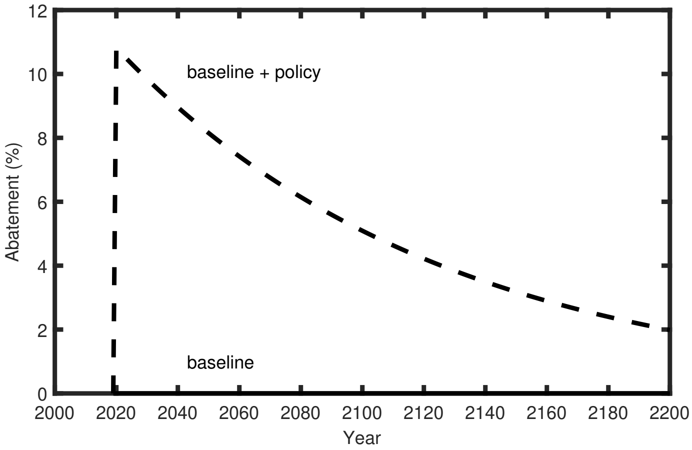


Figure 14: *Emissions tax: percentage abatement 2019-2200*

Once again, we assume a sudden increase in taxes to achieve the *ex ante* emission target in the long run. The emission tax in the technology baseline necessary to do so is 58 €, compared to 83 € when taxes are rebated to households as lump-sum transfers. This lower tax level is still effective in achieving the *ex ante* desired emissions reduction in the long run.

Moreover, the average subsidy for green investment totals 20% of the investment cost. This figure is slightly below recent findings by Darvas and Wolff (2021), who find that EU governments are willing to provide around 28% of the required funding for energy and transport investments in the energy transition.

Figure 15 depicts the evolution of emissions and the relative production of green to brown energy. Despite the significant fall in emissions, the impact on accumulated GDP during the transition period is virtually nil, as shown in Figure 16.

The final column in Table 3 indicates that the macro effects of this policy are consistent with those of subsidies on green investment and taxes on carbon implemented separately. This combination of emission taxes and green investment subsidies accounts for 89% of the emissions reduction compatible with the Green Deal target, and for the 77% of the NZE target. Furthermore, as shown in Table 4, this strategy mitigates most of the short-term welfare costs associated with financing green investment through lump sum taxes, as well as the long-term welfare costs of increasing carbon taxes and redistributing the revenues through transfers to households.

Comparing all the strategies, it can be concluded that this particular approach strikes a balance between short and long-term effects. It takes into consideration both immediate welfare concerns and the broader, long-term objectives of emission reduction and sustainable economic growth to a reasonable extent. Although this strategy in our model entails a relatively low welfare cost, it implies that the revenue from environmental taxation cannot be used to offset the unequal impact of these measures across households in the economy. The redistribution issue stands not only as an additional means to enhance welfare but, as emphasized by Blanchard, Gollier, and Tirole (2023), any effective environmental policy should encompass a redistribution component to mitigate the political costs associated with its implementation.

4..4 Full emissions target by 2050

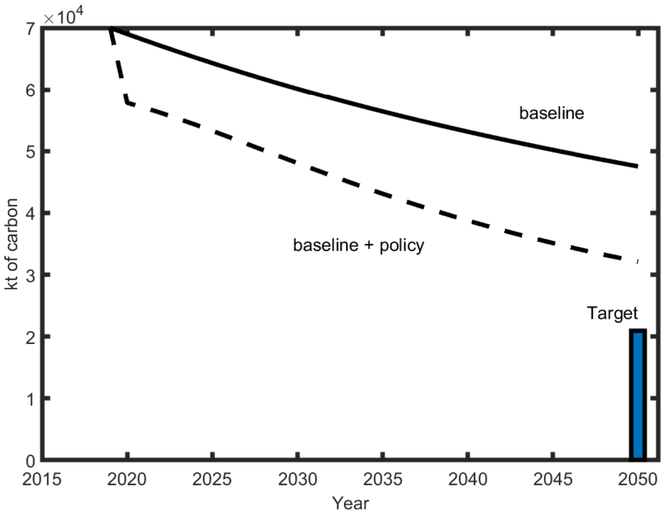
In the preceding section, we established a metric for comparing various mitigation policies. Nevertheless, as emphasized earlier, none of the proposed plans thus far are entirely capable of timely achieving the 2050 Net Zero Emissions (NZE) target.

This section aims to address several pivotal inquiries: What level of emissions tax would be necessary to successfully achieve the NZE target by 2050? What would be the corresponding welfare transition cost? Furthermore, in a scenario where the rest of the world reduces emissions at a pace akin to Spain's, what are the anticipated long-term benefits of this policy? We delve into these questions to offer comprehensive insights.

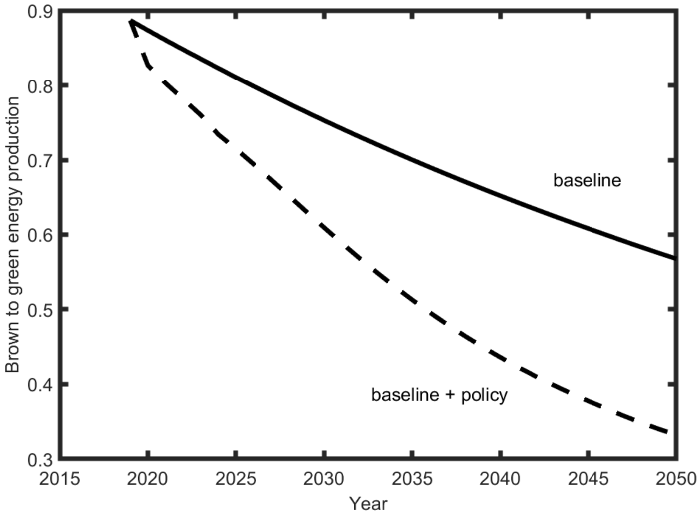
We now adopt a more realistic emissions tax scheme that increases linearly until 2050 and remains constant at this level thereafter. This tax trajectory is announced and fully anticipated by economic agents. Tax revenues are returned as lump-sum transfers to households. We simulate this anticipated policy alongside a sequence of unanticipated technological shocks corresponding to our baseline technology scenario.

The rest of the world's emissions were considered exogenous and constant so far. Now, we also consider a scenario where the rest of the world reduces emissions at the same rate as simulated in our economy while maintaining a constant ratio $\frac{e_t}{e_t^{row}}$ over time. We refer to this as a *coordinated* scenario. This term serves as a simplified representation of a fully general equilibrium coordinated scenario, wherein the costs incurred by the rest of the world due to mitigation policies would probably negatively affect the Spanish economy through various channels. Consequently, we interpret the coordinated welfare results as an upper bound.

Our results are displayed in Figure 17. Emissions taxes increase to a level of 227 € per tonne of carbon in 2050 to achieve NZE. Because the small weight of Spain in total emissions, the impact of the measure on the evolution of the global atmospheric carbon is negligible.



(a) *Carbon emissions. Baseline and emission taxes to subsidize green investment*



(b) *Brown to green energy production. Baseline and emission taxes to subsidize green investment.*

Figure 15: *Emission taxes used to subsidize green investment*

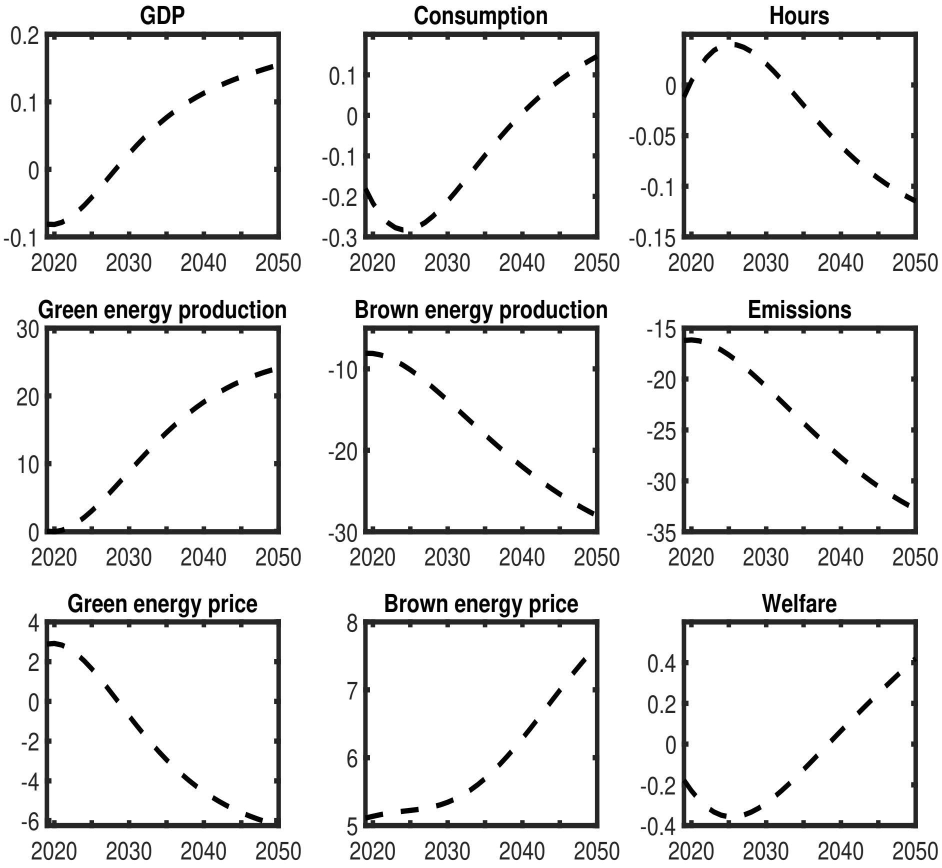


Figure 16: *Dynamic macroeconomic effects of a permanent unanticipated increase in the tax to emissions used to subsidize green investment (percentage deviations with respect to the baseline period)*

Using a standard assumption in the literature[19], we establish a mapping between the evolution of carbon atmospheric stock and temperature using the following expression:

$$T_t = \lambda \frac{\log(\frac{x_t}{\bar{x}})}{\log(2)} \tag{35}$$

Here, $\bar{x}$ stands for the pre-industrial atmospheric carbon concentration, and λ represents the sensitivity parameter of temperature to carbon stock. While a common value in the

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[19] See Golsov *et al.* (2014).

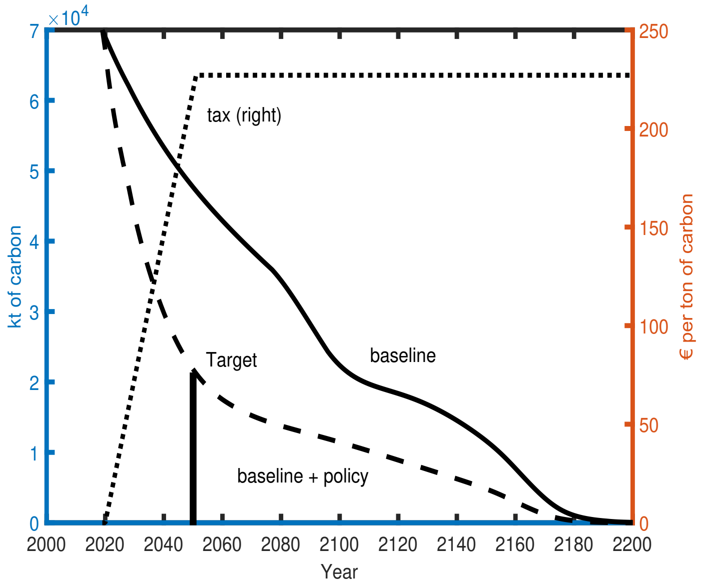

Figure 17: *Dynamic trajectory of emissions after an increase in emissions taxes. Baseline and baseline + policy scenarios (left scale). Taxes (right scale)*

literature has been $\lambda = 3$, we find that a value of $\lambda = 2.3$ better fits the historical relationship between carbon concentration and temperature since 1850.

Using this formula in a non-coordinated strategy, the temperature is projected to increase by 1.8 degrees Celsius above pre-industrial levels by 2050 [20], and by over 3.5 degrees Celsius by 2200 (Figure 18 and Table 5).

As a result of the economic impact of this policy, the average welfare loss relative to the technology baseline is estimated at -0.44% in terms of equivalent consumption during the period 2019-2050, and -19.11% between 2019 and 2200 (Figure 19 and Table 5).

In a coordinated scenario, the global emissions reduction gradually alters the trajectory of atmospheric carbon several decades into the implementation of the policy. Consequently, the increase in temperature above pre-idustrial levels will remain below 1.5 degrees Celsius by 2050 with excess temperature effectively reverting to almost pre-industrial levels by 2200. The beneficial impact on welfare is apparent, as depicted in Figure 19, although it takes several decades to materialize. In the very long run, there is an average welfare increase of 60% between 2019 and 2200 (refer to Table 5).

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[20] The temperature is considered to have been 1.1 degrees Celsius above pre-industrial levels in 2019.

4..5 Sensitivity analysis

In this section, we perform a robustness analysis of our findings by exploring the impact of different parameter changes within the environmental block of the model. To enable straightforward comparisons among these varied parameter settings, our emphasis will be on achieving the previously discussed full emissions target by 2050, accomplished via emissions taxation. As part of this approach, taxes will progressively rise in a linear fashion until 2050 and maintain a constant level thereafter for the long term.

Table 6 showcases the results concerning the average welfare impact during the transition period from 2019 to 2050. Initially, we present the welfare effects and the carbon tax projected for 2050 in the benchmark default case, as depicted in Table 5. This scenario reflects the parameter settings employed thus far and represents the no-coordination scenario. Within this context, the estimated welfare loss amounts to -0.44 percentage points in equivalent consumption between 2019 and 2050.

Next, we explore the scenario where the shift from dirty energy to clean energy becomes more challenging by reducing the elasticity of substitution between brown and green energy. Specifically, we halve the elasticity from the benchmark value of $\sigma^x = 3.94$ to $\sigma^x = 1.97$, aligning it more closely with the findings of Papageorgiou et al. (2017). To calculate the average welfare loss, we utilize expression (34), modifying the parameter in both the baseline and the baseline plus policy cases. This adjustment results in an increased carbon tax of 412 € per tonne of carbon by 2050. Consequently, welfare deteriorates compared to the benchmark scenario during the transition period, experiencing an average decrease of 0.55 percent.

When firms face a reduced elasticity of costs in relation to the share of abated emissions (θ_2^b), the costs of abatement for these firms may increase or decrease based on the initial value of μ_t^b. With lower initial values of μ_t^b, a decrease in θ_2^b amplifies the cost for the same change in μ_t^b. In our table, we have halved the value of θ_2^b from the benchmark of 2.8 to 1.4. This adjustment elevates the carbon tax to 287 € per tonne of carbon, which is 60 € higher than the baseline. However, this change does not affect the average welfare during this period.

The values of the parameters for the damage function are subject to high uncertainty. Therefore, we consider the case where the marginal damage to a change in atmospheric carbon stock is halved compared to the benchmark value. Specifically, we divide d_0 by 2. Despite this alteration, both the carbon price and welfare remain unaffected. This is attributed to the reduced impact of marginal damage, indicating that energy production has a less adverse effect on productivity, both before and after the implementation of carbon taxing. Moreover, considering Spain's limited influence on the global carbon

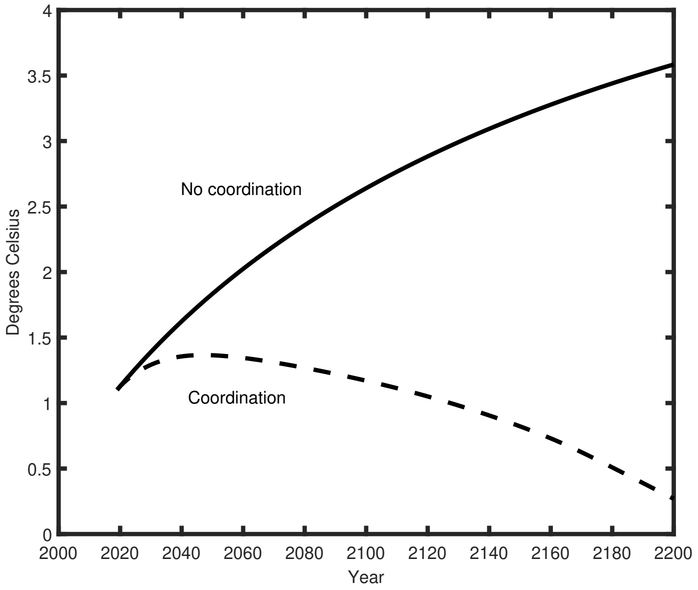

Figure 18: *Temperature evolution (above pre-industrial levels) between non-coordinated and coordinated scenarios*

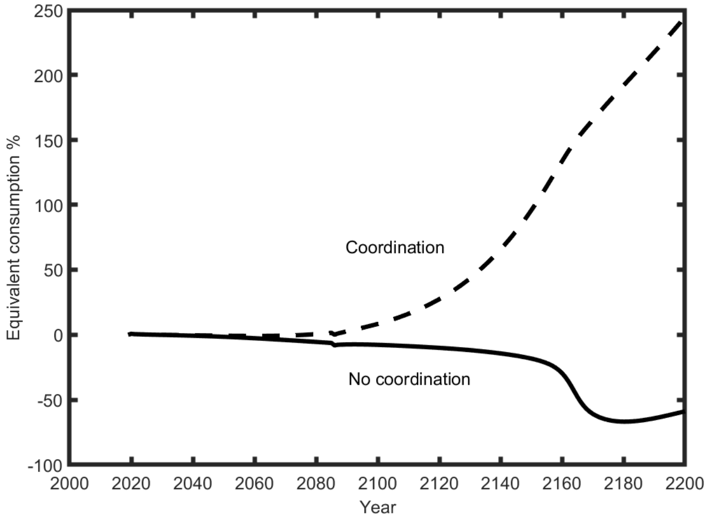

Figure 19: *Welfare evolution between non-coordinated and coordinated scenarios*

stock, this parameter adjustment has minimal impact on both carbon pricing and welfare.

We also examine the implications of doubling the marginal effect of dirty energy production on emissions via the parameter γ_1^b. This adjustment amplifies the influence

Welfare			
2019-2050		2019-2200	
No coordination	Coordination	No coordination	Coordination
-0.44	-0.18	-19.11	60.28

Temperature			
2050		2200	
No coordination	Coordination	No coordination	Coordination
1.83	1.36	3.58	0.27

Table 5: *Average welfare effects and temperature comparison (above pre-industrial levels) between non-coordinated and coordinated scenarios.*

of a carbon price increase on promoting abatement, as described by Equation 12. With heightened taxes, the relatively costlier dirty energy production becomes less appealing, prompting a more pronounced shift from dirty to cleaner energy sources. Table 6 illustrates that, in this scenario, the carbon tax by 2050 is half of the benchmark. However, despite this change, welfare remains unaffected.

Commencing with a lower elasticity of production to energy (1-α^y-β^y) reduces the welfare cost of achieving NZE. This circumstance arises from the fact that, in this scenario, the same level of emissions is produced using less energy, implying that brown energy is more polluting [21]. Substituting brown energy with green energy would consequently result in a more substantial reduction in emissions.

To gauge the impact of technology, we investigate a scenario where we switch off all three sources of technological progress. In this instance, the sole method to attain the 70% emission reduction by 2050 is through taxes. Consequently, the carbon tax will climb to 324 €, resulting in an average transition welfare decline of -0.65% in equivalent consumption.

Lastly, we reduce the value of the discount rate β from 4% to 2%. This adjustment causes the emission tax to rise to 313 €. However, the welfare cost decreases to -0.08%.

Although average welfare provides an overview, it conceals the trend in welfare losses over time. To offer a detailed insight into welfare's sensitivity to changes in environmental parameters, Figure 20 illustrates the period-to-period evolution of welfare losses. It showcases the benchmark scenario and the four scenarios from Table 6 that exhibit the most significant deviations in average welfare compared to the benchmark.

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[21] Calibrated emissions remain constant -equivalent to the observed ones- regardless of the values of the parameters α^y and β^y.

	Welfare 2019-2050	Carbon tax by 2050 €/tn carbon
Benchmark default	-0.44	227
Halving σ^x	-0.55	412
Halving θ_2^b	-0.42	287
Halving d_0	-0.45	227
Dubling γ_1^b	-0.44	114
Halving A_x	-0.43	220
Decreasing $\frac{\partial \ln y_t}{\partial \ln v_t^y}$ by 40%	-0.21	140
No technological progress	-0.65	324
Halving β	-0.08	313

Table 6: *Change in welfare and carbon tax to different environmental settings*

As expected due to the escalating trend in emission taxes, welfare effects depict a significant and persistent decline that extends well beyond the year 2050. By that juncture, the benchmark scenario records a welfare loss surpassing 1.5 percentage points (pp) in equivalent consumption. The sensitivity analysis uncovers a reduction of 0.6 pp in welfare loss by that year due to a lower elasticity of production to energy, an additional 0.4 pp welfare loss in the absence of technological growth, and a 0.7 pp increase in welfare loss when the elasticity of substitution between brown and green energy is more constrained.

Overall, the robustness analysis demonstrates that the welfare costs associated with transitioning to Net Zero Emissions (NZE) remain manageable across a wide range of simulation configurations.

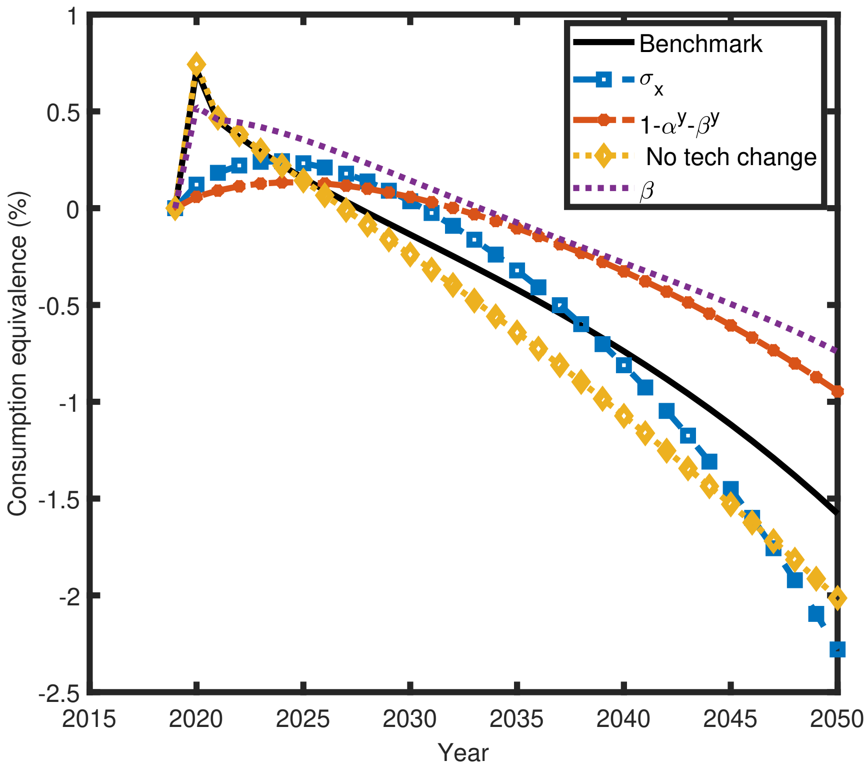

Figure 20: *Welfare evolution under different environmental parameters*

5. Conclusions

In this paper, we have proposed an environmental dynamic general equilibrium model to assess the welfare effects of energy transition policies, such as those geared to reduce carbon emissions through environmental taxation, investing in green technologies, or a combination of both. Starting from a central scenario characterized by a trend of environmentally friendly technological progress, zero-emission taxes and incentives to green investment, as well as current oil prices, we have simulated the effort required to achieve NZE under different mitigation strategies and assessing their welfare and macroeconomic consequences.

Maintaining or accelerating current emission-saving technological progress would reduce carbon emissions by one third by 2050 with respect to 2019. Policies heavily front-loaded to rapidly mitigate carbon emissions may demonstrate effectiveness in reaching the intermediate 2030 Green Deal target. However, they fall short of meeting the 2050 Net Zero Emissions (NZE). For example, a once-and-for-all subsidy on green energy investment of approximately 60% on green energy investment, equivalent to 2.6 percentage points of GDP per year in government budget costs, would result in reaching 92% of the intermediate 2030 target but only 80% of the 2050 NZE target.

The welfare effects significantly vary between the short to medium and the very long term, particularly among different mitigation policies. Thus, elevating fossil fuel prices to deter their usage results in the highest welfare costs in both the transition to 2050 and in the long run. Conversely, emissions taxes prove to be the most favorable policy in terms of welfare during the transition to 2050, while green investment subsidies exhibit substantial welfare gains in the very long term, even without a globally coordinated emissions reduction policy.

To attain Net Zero Emissions (NZE) fully, a gradual increase in the carbon tax to a steady state level of 227 € per tonne of carbon (at 2010 prices) is needed. The average welfare loss resulting from this policy is calculated at a very manageable -0.44% in terms of equivalent consumption during the period 2019-2050. However, it escalates to -19.11% in the very long run (between 2019 and 2200). When the government reallocates revenues from carbon taxes towards green investment subsidies, the required increase in the tax to achieve the emission target is significantly lower. Additionally, this policy leads to a more balanced welfare effect between the short and long run.

Our findings highlight the significance of global coordination in mitigation policies. Through a simple exercise, we demonstrate that a coordinated policy possesses the potential to entirely reverse the long-term adverse effects of emission taxes, transforming them from negative to largely positive impacts. This transformation occurs via a substantial reversal in the global temperature trend.

Overall, our paper underscores the utility of eDGE models for assessing the welfare and macroeconomic consequences of various mitigation policies across different scenarios and assumptions, particularly in light of the uncertainties surrounding energy transition, technological advancements, and climate change.

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Appendix A The complete Model

In this Appendix, we show all the equations of the model

$$\lambda_t = \frac{1}{c_t^{\sigma}} \tag{36}$$

$$\kappa_L h_t^{\varphi} = \lambda_t w_t \tag{37}$$

$$\lambda_t = \beta \mathbb{E}_t \left(\lambda_{t+1} \frac{r_t}{\pi_{t+1}} \right) \tag{38}$$

$$q_t^s = \beta \mathbb{E}_t \left\{ \left(\frac{\lambda_{t+1}}{\lambda_t} [r_{t+1}^s + (1-\delta_s) q_{t+1}^s] \right) \right\} \quad \text{for } s = \{y, g, b\} \tag{39}$$

$$\begin{aligned} 1 - \tau_t^{i^s} &= q_t^s \left[1 - \kappa_I^s \left(\frac{i_t^s}{i_{t-1}^s} \right) \left(\frac{i_t^s}{i_{t-1}^s} - 1 \right) - \frac{\kappa_I^s}{2} \left(\frac{i_t^s}{i_{t-1}^s} - 1 \right)^2 \right] \\ +\kappa_I^s \beta \mathbb{E}_t &\left\{ q_{t+1}^s \frac{\lambda_{t+1}}{\lambda_t} \left[\left(\frac{i_{t+1}^s}{i_t^s} - 1 \right) \left(\frac{i_{t+1}^s}{i_t^s} \right)^2 \right] \right\} \quad \text{for } s = \{y, g, b\} \text{ and } \tau_t^{i^s} = 0 \text{ for } s = \{y, b\} \end{aligned} \tag{40}$$

$$k_t^y = (1-\delta_y) k_{t-1}^y + \left[1 - \frac{\kappa_I^y}{2} \left(\frac{i_t^y}{i_{t-1}^y} - 1 \right)^2 \right] i_t^y \tag{41}$$

$$k_t^g = (1-\delta_g) k_{t-1}^g + \left[1 - \frac{\kappa_I^g}{2} \left(\frac{i_t^g}{i_{t-1}^g} - 1 \right)^2 \right] i_t^g \tag{42}$$

$$k_t^b = (1-\delta_b) k_{t-1}^b + \left[1 - \frac{\kappa_I^b}{2} \left(\frac{i_t^b}{i_{t-1}^b} - 1 \right)^2 \right] i_t^b \tag{43}$$

$$v_t^g = \varsigma_t^g \left(k_{t-1}^g \right)^{\alpha^g} \tag{44}$$

$$v_t^b = \varsigma_t^b \left(k_{t-1}^b \right)^{\alpha^b} \left(m_t^b \right)^{1-\alpha^b} \tag{45}$$

$$e_t^b = \left(1 - \mu_t^b \right) \gamma_{1t}^b \left(v_t^b \right)^{1-\gamma_2^b} \tag{46}$$

$$z_t^b = \theta_1^b \left(\mu_t^b\right)^{\theta_2^b} v_t^b \tag{47}$$

$$p_t^{v^g} = \frac{r_t^g}{\alpha^g \varsigma_t^g} \left(k_{t-1}^g\right)^{1-\alpha^g} \tag{48}$$

$$p_t^{v^b} = \frac{r_t^b}{\alpha^b \varsigma_t^b} \left(\frac{k_{t-1}^b}{m_t^b}\right)^{1-\alpha^b} + \frac{\tau_t^e \left(1-\mu_t^b\right) \gamma_{1t}^b \left(1-\gamma_2^b\right)}{\left(v_t^b\right)^{\gamma_2^b}} + \theta_1^b \left(\mu_t^b\right)^{\theta_2^b} \tag{49}$$

$$p_t^{v^b} = \frac{(1+\tau_t^m) p_t^{*m^b}}{(1-\alpha^b)\, \varsigma_t^b} \left(\frac{m_t^b}{k_{t-1}^b}\right)^{\alpha^b} + \frac{\tau_t^e \left(1-\mu_t^b\right) \gamma_{1t}^b \left(1-\gamma_2^b\right)}{\left(v_t^b\right)^{\gamma_2^b}} + \theta_1^b \left(\mu_t^b\right)^{\theta_2^b} \tag{50}$$

$$\mu_t^b = \left[\frac{\tau_t^e \gamma_{1t}^b}{\theta_1^b \theta_2^b} \left(v_t^b\right)^{-\gamma_2^b}\right]^{\frac{1}{\theta_2^b - 1}} \tag{51}$$

$$e_t = e_t^b \tag{52}$$

$$\tilde{v}_t{}^y = \left[\theta^g \left(v_t^g\right)^{\frac{\sigma^x - 1}{\sigma^x}} + (1-\theta^g) \left(v_t^b\right)^{\frac{\sigma^x - 1}{\sigma^x}}\right]^{\frac{\sigma^x}{\sigma^x - 1}} \tag{53}$$

$$v_t^y = A_t^x \tilde{v}_t{}^y \tag{54}$$

$$v_t^g = (\theta^g)^{\sigma^x} \left(\frac{p_t^{v^g}}{p_t^{v^y}}\right)^{-\sigma^x} \frac{v_t^y}{\left(A_t^x\right)^{1-\sigma^x}} \tag{55}$$

$$v_t^b = (1-\theta^g)^{\sigma^x} \left(\frac{p_t^{v^b}}{p_t^{v^y}}\right)^{-\sigma^x} \frac{v_t^y}{\left(A_t^x\right)^{1-\sigma^x}} \tag{56}$$

$$\left(\pi_t - \bar{\pi}\right) \pi_t = \frac{(1-\sigma^r)}{\kappa_p} + \frac{\sigma^r}{\kappa_p} mc_t + \beta \mathbb{E}_t \frac{\lambda_{t+1}}{\lambda_t} \left(\pi_{t+1} - \bar{\pi}\right) \pi_{t+1} \frac{y_{t+1}}{y_t} \tag{57}$$

$$r_t^y = \alpha^y mc_t \frac{y_t}{k_{t-1}^y} \tag{58}$$

$$w_t = \beta^y mc_t \frac{y_t}{h_t} \tag{59}$$

$$p_t^{v^y} = (1 - \alpha^y - \beta^y)\, mc_t \frac{y_t}{v_t^y} \tag{60}$$

$$y_t = A_t^y \left(k_{t-1}^y\right)^{\alpha^y} {h_t}^{\beta^y} \left(A_t^x {\tilde{v}_t}^y\right)^{1-\alpha^y-\beta^y} \tag{61}$$

$$\Gamma_t^y = y_t \left(1 - mc_t - \frac{\kappa_p}{2}\left(\pi_t - -\bar{\pi}\right)^2\right) \tag{62}$$

$$\Gamma_t^{v^g} = (1 - \alpha^g) p_t^{v^g} v_t^g \tag{63}$$

$$\Gamma_t^{v^b} = -\tau_t^e \gamma_2^b e_t^b \tag{64}$$

$$x_t = \eta x_{t-1} + e_t + e_t^{row} \tag{65}$$

$$A_t^y = [1 - (d_0 + d_1 x_t + d_2 x_t^2] \tilde{A}_t^y \tag{66}$$

$$g_t + \tau_t^{i^g} i_t^g = \tau_t^h + \tau_t^m p_t^{*m^b} m_t^b + \tau_t^e e_t \tag{67}$$

$$\frac{r_t}{r} = \left(\frac{r_{t-1}}{r}\right)^{\rho_r} \left[\left(\frac{\pi_t^{EZ}}{\pi^{EZ}}\right)^{\phi_\pi} \left(\frac{y_t^{EZ}}{y^{EZ}}\right)^{\phi_y}\right] \exp\left(\nu_t^r\right) \tag{68}$$

$$\pi_t^{EZ} = 0.1\pi_t + 0.9{\pi_t^*}^{REZ} \tag{69}$$

$$y_t^{EZ} = 0.1 y_t + 0.9{y_t^*}^{REZ} \tag{70}$$

$$y_t = c_t + i_t^y + i_t^g + i_t^b + g_t + p_t^{*m^b} m_t^b + \theta_1^b \left(\mu_t^b\right)^{\theta_2^b} v_t^b + \frac{\kappa_p}{2}\left(\pi_t - \bar{\pi}\right)^2 y_t \tag{71}$$

$$U_t = \left(\frac{c_t^{1-\sigma}}{1-\sigma} - \kappa_L \frac{h_t^{1+\varphi}}{1+\varphi}\right) \tag{72}$$

$$W_t = U_t + \beta \mathbb{E}_t W_{t+1} \tag{73}$$

40 equations for 40 variables (definitions not included):

Transitioning to Net-Zero: Welfare Assessment

λ_t, c_t, h_t, w_t, r_t, π_t, q_t^y, q_t^g, q_t^b, r_t^y, r_t^g, r_t^b, i_t^y, i_t^g, i_t^b, k_t^y, k_t^g, k_t^b, m_t^b, v_t^g, v_t^b, v_t^y, $\tilde{v}_t{}^y$, e_t^b, e_t, μ_t^b, z_t^b, $p_t^{v^g}$, $p_t^{v^b}$, $p_t^{v^y}$, mc_t, y_t, A_t^y, Γ_t^y, x_t, τ_t^h, U_t, W_t

Appendix B Parameter values and macroeconomic ratios

This appendix presents the values of the parameters and exogenous variables used in the model (Table B1) as well as the performance of the model in matching selected energy and macroeconomic ratios (Table B2).

Table B1: *Value of the parameters and benchmark values of the exogenous variables*

Parameter	Value	Description
β	0.9615	Preference discount rate
σ	1.4286	Intertemporal elasticity consumption
φ	2.5000	Intertemporal elasticity leisure
δ_y	0.0443	Depreciation of capital for the production of goods
δ_g	0.0414	Depreciation of capital for the production of green energy
δ_b	0.0327	Depreciation of capital for the production of brown energy
κ_I^y	15.000	Adjustment cost of capital for the production of goods
κ_I^g	20.000	Adjustment cost of capital for the production of green energy
κ_I^b	20.000	Adjustment cost of capital for the production of brown energy
α^g	0.5000	Capital elasticity in the production of green energy
α^b	0.5000	Capital elasticity in the production of brown energy
γ_1^b	0.8386	Scaling parameter in the emission function
γ_2^b	0.0000	Elasticty parameter in the emission funtion
θ_1^b	1.3400	Scaling parameter in the cost of abatement function
θ_2^b	2.8000	Elasticity parameter in the cost of abatement function
σ^x	3.9400	Elasticity of substitution in the energy mix
θ^g	0.4670	Distribution parameter in the energy mix
κ_L	39.207	Work disutility
$\bar{\pi}$	1.0000	Inflation rate in the steady state
σ^r	6.2632	Elasticity of substitution in intermediate goods
κ_p	0.001	Price rigidity parameter
α^y	0.5036	Capital elasticity in the production of goods
β^y	0.4264	Labor elasticity in the production of goods
η	0.9964	Natural absorption of atmospheric carbon
d_0	$4.1064e-04$	Parameter in the damage function
d_1	1.0032	Parameter in the damage function
τ	0.0000	Tax per unit of emissions
t^{ig}	0.0000	Green energy investment subsidy
t^m	0.0000	Green energy demand subsidy
A^x	1.0000	TFP in the production of the mix of energy
$\tilde{A}^y$	0.8368	TFP in the production of goods
ν^g	0.2370	TFP in the production of green energy
ν^b	1.0193	TFP in the production of brown energy
λ	2.3000	Reaction of temperature to carbon concentration

Table B2: *Energy and macroeconomic ratios*

Ratios (energy)	Model	Target
Energy intensity (kt oil equivalent per million € GDP)	0.0950	0.0950
Emissions (kt carbon per million € GDP)	0.0717	0.0717
Stock of carbon (kt of carbon per million € GDP)	775.8841	775.8841
Carbon intensity (kt of carbon per kt of oil equivalent)	0.7664	0.7664
Green energy to brown energy production	1.1277	1.1277
Share of energy to produce energy	0.2553	–
Share of green energy in the energy mix	0.4894	–
Share of brown energy in the energy mix	0.5106	–
Ratios (other)	Model	Target
Consumption over GDP	0.5600	0.5600
Investment over GDP	0.2400	0.2400
Government consumption over GDP	0.2000	0.2000
Working hours over total hours	0.3333	0.3333
Investment in green energy over total investment	0.0310	0.0310
Investment in brown energy over total investment	0.0286	0.0286
Rental rate of capital for goods	0.0843	–
Rental rate of capital for green energy	0.0814	–
Rental rate of capital for brown energy	0.0727	–

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