Net-Zero Transition and Welfare in General Equilibrium*

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Abstract

This study examines the welfare implications of different carbon mitigation strategies using a dynamic general equilibrium model. The model captures the production of goods and services using energy derived from green renewable technologies and fossil fuels that emit CO2. We establish a model-implied baseline scenario, as well as optimistic and pessimistic scenarios, reflecting decarbonization technologies that align with observed trends in GDP, carbon emissions, and the clean to dirty energy production ratio from 2010-2019. We set an emission reduction target for 2050, consistent with the Paris Agreement, and study the welfare and macroeconomic effects of different policies that would complement technological progress. Our findings indicate that emission taxes have the least harmful impact during the transition period until the target is achieved, while subsidies on green investment have the most beneficial long-term effects on welfare. A policy that uses government revenues from carbon taxes to subsidize green investment strikes a balance between the short and long run, with minimal social welfare loss. Emissions taxes are projected to increase by approximately €60 in the central scenario, but this value falls to €48 if tax revenues are used to subsidize green investment. However, without technological progress, the price of carbon would increase by over €125. These three policies welfare-dominate the strategy of guaranteeing a path of increasing the price of fossil fuels over time. We also show that a degrowth strategy aimed at net-zero emissions has significant costs in terms of welfare, even after accounting for changes in preferences.

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

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1. Introduction

The transition to a low-carbon economy is a pressing global challenge in the face of climate change (IPCC, 2018). In line with the Paris Agreement (UNFCCC, 2015), the International Energy Agency (IEA, 2020) has established a normative scenario of achieving Net Zero Emissions (NZE) by 2050, with advanced economies leading the way towards this target. The implementation of effective economic policies to facilitate this transition will affect the aggregate dynamics of these economies in a way that is better understood within the framework of Dynamic General Equilibrium (DGE) models designed to capture the interplay between climate change and economic growth (see, for example, Nordhaus, 1991, or Annicchiarico et al 2021).

In this study, we assess the transition to a low-emissions economy in an E-DGE (environmental DGE) model that incorporates energy-related inputs as well as the cost of reducing emissions. We analyze the macroeconomic effects of different policies, such as subsidies and taxes, aimed at mitigating emissions and promoting the adoption of green energy technologies (Semmler et al., 2021 and Marron and Toder, 2014). We also examine how technological change can help to reduce the intensity of brown energy and increase the efficiency of the energy mix (Nakicenovic and Swart, 2000). Furthermore, we consider the role of investment in energy capital as a key driver of this transition (Jackson and Jackson, 2021).

The aim of this paper is to contribute to the existing literature on the intricate relationships among technology, fiscal policy, and the energy transition. The model developed in this paper considers energy consumption in the production of goods and services. This energy can be derived from either green renewable technologies or fossil fuels that emit CO2 (referred to as dirty or brown technologies). By incorporating this energy mix, we examine the implications of decarbonization, specifically the shift from brown to green energy. This transition can be facilitated through the subsidization of green capital investment. Additionally, the model incorporates various forms of energy efficiency improvements and environmental taxes on emissions. To calibrate the model, we utilize data from the Spanish economy for the year 2010 as the base year. Through the lens of this dynamic general equilibrium model, we provide valuable insights into the trade-offs and synergies between economic growth and environmental sustainability. Furthermore, we explore the economic consequences of different decarbonization strategies for the Spanish economy.

We specifically analyze the case of Spain in our study, but we also examine an international coordinated scenario using simplified assumptions. In this scenario, we make use of a shortcut where we assume that the rest of the world is composed of an identical economy to Spain, implementing the same policies and achieving the same level of emissions output. We also abstract from the economic consequences of any interactions between Spain and the rest of the world. By employing this simplified approach, we aim to gain insights into the potential environmental and economic benefits of an extension of the policies under investigation.

Related literature ... (TBC)

The structure of the paper is as follows. Section 2 presents the model. Section 3 shows the calibration strategy. Section 4 presents the simulation exercises and, finally, section 5 concludes.

2. The Model

The economy produces goods and services using labor, capital, and energy. The production process is structured into different levels. The lowest level represents energy producers that use specific capital to generate energy, resulting in CO2 emissions with different intensities depending on whether they use green or brown technology. Brown energy producers also import a fossil fuel commodity at a given international price. This price can be affected by international market fluctuations or by introducing tariffs. Firms can invest in reducing emissions but incur a cost to do so, and emissions can also be subject to a tax. Technology improvements in the use of fossil fuels help decarbonize the economy.

The next level up represents energy distribution firms that buy green and brown energy from energy producers and package it into a bundle that they sell to intermediate goods producers. The selling price of the energy bundle depends on the energy mix. Technological progress biased towards green energy production contributes to reducing carbon emissions.

At the intermediate goods level, firms use labor, capital, and energy from the energy package to produce a variety of goods under monopolistic competition. Each variety faces a downward sloping demand curve, and firms incur costs for changing prices, resulting in sticky prices. Finally, at the top level, firms package a variety of intermediate goods and sell a homogeneous product for consumption, investment, and public spending.

Households offer labor services and use their income to buy consumption goods and invest in different capital goods. Investment in green capital may be subsidized by the government. The government can establish mitigation plans by subsidizing green investment, introducing tariffs to fossil fuel imports, or taxing emissions.

Next, we provide an overview of our economic 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 their consumption (c_t) and working hours (h_t). The households are also the owners of the firms in the economy. They earn income from supplying labor hours in the labor market, 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), yields on government bonds (r_t), and profits obtained from owning firms in green energy production (Γ_t^{vg}), brown energy production (Γ_t^{vb}), and goods and services production (Γ_t^{y}). 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). The government has the option of subsidizing households' investment in green capital (t_t^{ig}) and collects a lump-sum tax (or pays a subsidy) every period to balance its budget (t_t).

The representative household solves,

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

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

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

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

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

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 with specific capital using the following technology:

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

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

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

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

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 and concave 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 $\gamma_2^b < 1$ and γ_{1t}^b controls 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 can be obligated to pay a tax τ_t per unit of emissions. The existence of a cost for emitting carbon to 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 brown energy producers' abatement costs 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:

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

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

and

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

$$\max_{k_{t-1}^b, m_t^b, \mu_t^b} \quad P_t^{v^b} v_t^b - P_t r_t^b k_{t-1}^b - (1 + t_t^m) P_t^{*m^b} m_t^b - P_t \tau_t e_t^b - P_t \theta_1^b \left(\mu_t^b\right)^{\theta_2^b} v_t^b \qquad s.t$$

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

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

where $P_t^{v^l}$ is the price of type-l energy, $P_t^{*m^b}$ is the exogenous price of the imported energy commodity, and t_t^m is an exogenous price shifter, tipically 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

$$\mu_t^b = \left[\frac{\tau_t \gamma_{1t}^b}{\theta_1^b \theta_2^b} \left(v_t^b \right)^{-\gamma_2^b} \right]^{\frac{1}{\theta_2^b - 1}} \tag{12}$$

Without internalizing 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.

$$\Gamma_t^{v^g} = (1 - \alpha^g) p_t^{v^g} v_t^g \tag{13}$$

$$\Gamma_t^{v^b} = -\tau_t \gamma_2^b e_t^b \tag{14}$$

2..3 Energy distributors

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

$$v_t^y = A_t^x \left[\theta^g \left(v_t^g \right)^{\frac{\sigma^x - 1}{\sigma^x}} + (1 - \theta^g) \left(v_t^b \right)^{\frac{\sigma^x - 1}{\sigma^x}} \right]^{\frac{\sigma^x}{\sigma^x - 1}} \tag{15}$$

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

Define $\tilde{v}_t{}^y = \left[\theta^g \left(v_t^g \right)^{\frac{\sigma^x - 1}{\sigma^x}} + (1 - \theta^g) \left(v_t^b \right)^{\frac{\sigma^x - 1}{\sigma^x}} \right]^{\frac{\sigma^x}{\sigma^x - 1}}$ the use of energy. Then rewrite (15) as,

$$v_t^y = A_t^x \tilde{v}_t{}^y \tag{16}$$

where A_t^x represents the efficiency in the distribution of energy.

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

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

where ς_t^g and ς_t^b can be interpreted as technical change biased towards the demand for green and brown capital in the production of the energy mix. An increase in the ratio $\frac{\varsigma_t^g}{\varsigma_t^b}$ contributes to faster decarbonization caused by the change in the energy mix from brown energy to green energy.

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.

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

Using equation (11) and the FOCs it can be shown that 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

$$p_t^{v^y} = \frac{1}{A_t^x} \left[(\theta^g)^{\sigma^x} \left(p_t^{v^g} \right)^{1-\sigma^x} + (1 - \theta^g)^{\sigma^x} \left(p_t^{v^b} \right)^{1-\sigma^x} \right]^{\frac{1}{1-\sigma^x}} \tag{19}$$

2..3.1 Intermediate goods 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 ($v_t^y(i)$),

$$y_t(i) = A_t^y(i) k_{t-1}^y(i)^{\alpha^y} h_t(i)^{\beta^y} v_t^y(i)^{1-\alpha^y-\beta^y} \tag{20}$$

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

Introducing (16) into (20) we get,

$$y_t(i) = A_t^y(i) k_{t-1}^y(i)^{\alpha^y} h_t(i)^{\beta^y} \left(A_t^x \tilde{v}_t{}^y(i) \right)^{1-\alpha^y-\beta^y} \tag{21}$$

A higher A_t^x represents an increase in the efficiency of energy distribution, which means that energy is distributed with less waste, resulting in lower energy consumption to produce a unit of output.

Firms face a downward sloping demand curve

$$y_t(i) = \left(\frac{P_t(i)}{P_t} \right)^{-\sigma^r} y_t \tag{22}$$

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

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

$$AC_t(i) = \frac{\kappa_p}{2}\left(\frac{P_t(i)}{P_{t-1}(i)} - \bar{\pi}\right)^2 P_t y_t \tag{23}$$

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:

$$\Gamma^y_t = y_t\left(1 - mc_t - \frac{\kappa_p}{2}(\pi_t - -\bar{\pi})^2\right) \tag{24}$$

2..3.2 Final-good firms

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

$$y_t = \left[\int_a^b y_t(i)^{\frac{\sigma^r-1}{\sigma^r}}di\right]^{\frac{\sigma^r}{\sigma^r-1}} \tag{25}$$

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

The optimization problem is,

$$\max_{y_t(i)} P_t y_t - \int_a^b P_t(i)y_t(i)di \tag{26}$$

and profits at this level of production are zero.

2..4 Environmental and economic damage

Emissions feed the atmospheric carbon stock, x_t,

$$x_t = \eta_t x_{t-1} + e_t + e_t^{row} \tag{27}$$

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, which can be exogenously modify by means of carbon dioxide removal (CDR) technologies.

Atmospheric carbon stock damages total factor productivity [2] as follows

$$A_t^y = [1 - (d_0 + d_1 x_t + d_2 x_t^2)]\widetilde{A}_t^y \tag{28}$$

The economic cost of CO2 accumulation is convex, as in Dietz and Stern (2015), if $d_2 > 0$, and $\widetilde{A}_t^y$ 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:

$$\widetilde{A}_t^y = \widetilde{A}_0^y \left(1 + g_{\widetilde{A}}\right)^t \tag{29}$$

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

2..5 Government and the Central Bank

The central bank follows a standard Taylor's rule,

$$\frac{r_t}{r} = \left(\frac{r_{t-1}}{r}\right)^{\rho_r} \left[\left(\frac{\pi_t}{\pi}\right)^{\phi_\pi} \left(\frac{y_t}{y}\right)^{\phi_y}\right] \tag{30}$$

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 (t_t^{ig}) by levying lump sum taxes on households (t_t), tariffs on the imported energy commodity ($t_t^m p_t^{*m^b} m_t^b$), and emission taxes on energy-producing firms (τ_t). So, the budget constrain can be written as,

[2] Although Spain contributes only to a small part of world emissions and, hence, the impact on carbon stock and on the economic damage of environmental measures implemented in Spain is expected to be almost negligible, considering a damage function is still important for our coordination scenario, in which the rest of the world achieves the same environmental results as Spain.

$$g_t + t_t^{ig} i_t^g = t_t + t_t^m p_t^{*m^b} m_t^b + \tau_t e_t \tag{31}$$

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

$$y_t = c_t + i_t^y + i_t^g + i_t^b + g_t + p_t^{*m^b} m_t^b + \theta_1^b \left(\mu_t^b\right)^{\theta_2^b} v_t^b + \frac{\kappa_p}{2} \left(\pi_t - \bar{\pi}\right)^2 y_t \tag{32}$$

3. Calibration

We calibrate the model annually to replicate certain energy and environmental ratios of the Spanish economy in 2010. 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. On the other hand, 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 (kt) 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 regarding 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

The value of the elasticity of substitution between green and brown energy, $\sigma^x = 3.94$, comes from Table 2 in Stockl and Zerrahn (2020). [3] We adopt the parameter for the convex capital adjustment cost function, $\kappa_I^y = 15$, from Annicchiarico and di Dio (2015). Given the characteristics of energy capital, we assume that adjustment costs for the capital used in energy production are higher than the average adjustment cost. Specifically, we consider these costs to be 1/3 higher than the adjustment costs for 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 U.S. Energy Information Administration (2022). Based on this report, we set $1 - \alpha^y - \beta^y = 0.07$. [4]

3..2 Parameters from empirical evidence, model equations and exogenous variables

We determine the value of α^b based on two shares. Firstly, 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. By calibrating the static version of the model equations, we simultaneously match the energy intensity per unit of GDP and the ratio between the prices of green and brown energy in 2010, resulting in calibrated values of $\delta_b = 3.27\%$ and $\delta_g = 4.14\%$. Energy intensity is calculated by dividing the energy consumption in kilotonnes of oil equivalent by the million euros of production, using data from Eurostat (2022). Additionally,

[3] This can be regarded as the central value from a range of various scenarios.
[4] In the Energy Overview category, specifically Section 1.5, the energy expenditure as a share of GDP was reported as 8.1%. We consider Spain to be slightly less energy-intensive than the U.S.
[5] Eurostat: Energy Statistics - An Overview
[6] El Sistema Eléctrico Español. Informe 2019

our target is to achieve a price ratio of 85% between green and brown energy, $\frac{p^{vg}_{2010}}{p^{vb}_{2010}}$.[7] The findings regarding depreciation rates indicate that energy infrastructure generally has a longer useful life compared to capital used in the production of goods, with capital for dirty energy production having the longest lifespan. 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 $\tau = t^{ig}_{2010} = t^{m}_{2010} = 0$ (no taxes or subsidies). To align with the observed production of green and brown energy in 2010, we calibrate $\nu^b_{2010} = 0.0884$ and $\nu^g_{2010} = 0.0997$. Additionally, we normalize $A^x_{2010} = 1.0$ and 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.

3..3 The damage function

Heutel (2012) calibrates the coefficients in the quadratic damage function, $d(x) = d_0 + d_1 x + d_2 x^2$, based on the DICE-2007 model by Nordhaus (2008). We adjust these values to fit our normalization of total production and the units for x in kilotonnes.

Figure 1 represents how this function varies with the stock of atmospheric carbon, and specifically marks the values corresponding to the 2010 benchmark year. For the atmospheric carbon mass of approximately 776 kt per million of Spanish GDP in 2010, this corresponds to a TFP loss of 0.6%. Increasing the atmospheric carbon mass by 50% leads to a TFP loss of 1.7%.

3..4 Atmospheric carbon accumulation

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

$$x_t = \eta_t x_{t-1} + e_t + e^{row} \tag{33}$$

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 different estimates for this parameter, making it challenging to determine a precise value. Moore and Braswell (1994) estimate the half-life of atmospheric CO2 to be between 19 and 92 years under various assumptions. Heutel (2012) assumes a half-life of 83 years, which corresponds to a quarterly parameter η of 0.9979.

[7] According to Covert, Greenstone, and Knittel (2016), the levelized cost of generating nuclear and wind energy has fallen below coal energy since 2010 and rapidly converged towards gas

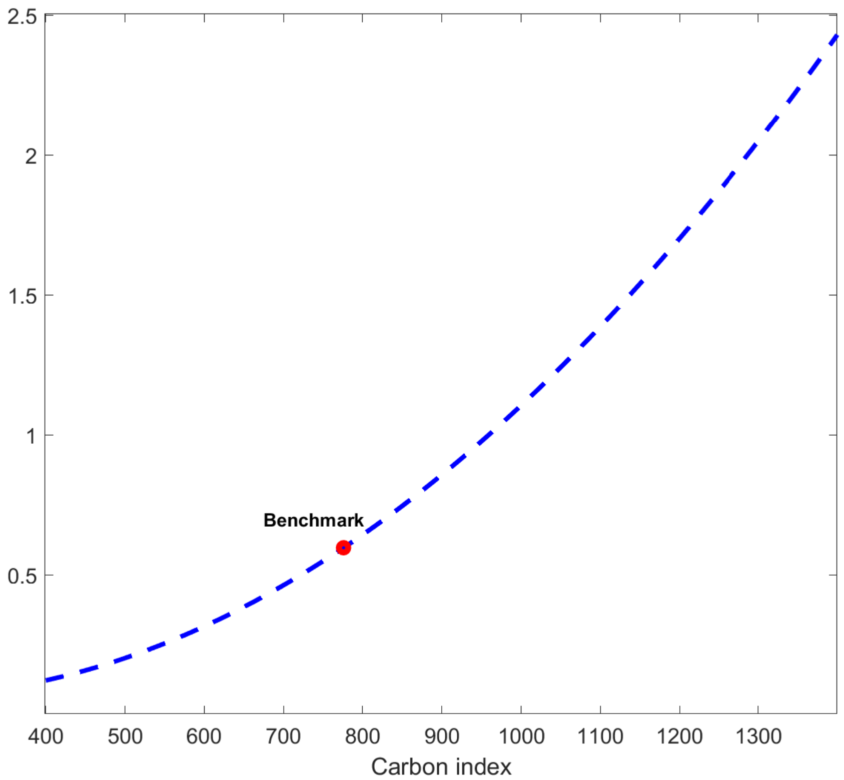


Figure 1: *Economic cost (% of TFP) as a function of atmospheric carbon*

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. By using Equation (33), we can determine a yearly parameter $\eta = 0.9879$ consistent with an steady state.

This value indicates that terrestrial ecosystems absorb approximately 30% of global emissions in 2021, consistent with observations over the past 50 years (see Brienen et al., 2020). Furthermore, it implies that the transition between two steady states takes approximately $1/(1-\eta) = 85$ years, and the average half-life of atmospheric carbon is 59 years ($-log(2)/log(\eta)$).

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

3..5 Emissions

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

$$et = (1 - \mu t)\gamma_1 y^{1-\gamma 2} t$$

Here, μ_t 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 and brown energy production in 2010, γ_1^b should satisfy the equation:

$$\gamma_1^b = \frac{e_{2010}^b}{\left(v_{2010}^b\right)^{1-\gamma_2^b}} \tag{34}$$

Furthermore, Sen and Vollebergh (2018) estimate that a 1 € increase in energy taxes imposed on each tonne of CO2 leads to a long-run reduction in emissions from energy consumption by 0.73%. Therefore, we calibrate γ_2 (and consequently, γ_1^b from equation (34)) to ensure that the model generates an average 0.73% reduction in emissions following a 1 € increase in the carbon tax per tonne of CO2 (equivalent to 3.67 per tonne of carbon). The relationship between emissions and normalized output is illustrated in Figure 2.

3..6 Abatement costs

The ratio $z(\mu_t)/y_t$ represents the cost of reducing a fraction μ_t of emissions relative to total output. Heutel (2012) assumes a parameter elasticity of the cost of abatement, $\theta_2 = 2.8$, based on Nordhaus (2008). We adopt the same elasticity. Regarding the scale coefficient, Heutel (2012) sets $\theta_1 = 0.05607$, indicating that completely 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 $\theta_1 = 0.185$. To reconcile these differences, we choose θ_1 such that it results in a cost of 12% for $\mu_t = 1$, 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.

Figure 3 illustrates the relationship between the cost and the percentage of abated emissions for the benchmark level of dirty energy production. Note that due to the uncer-

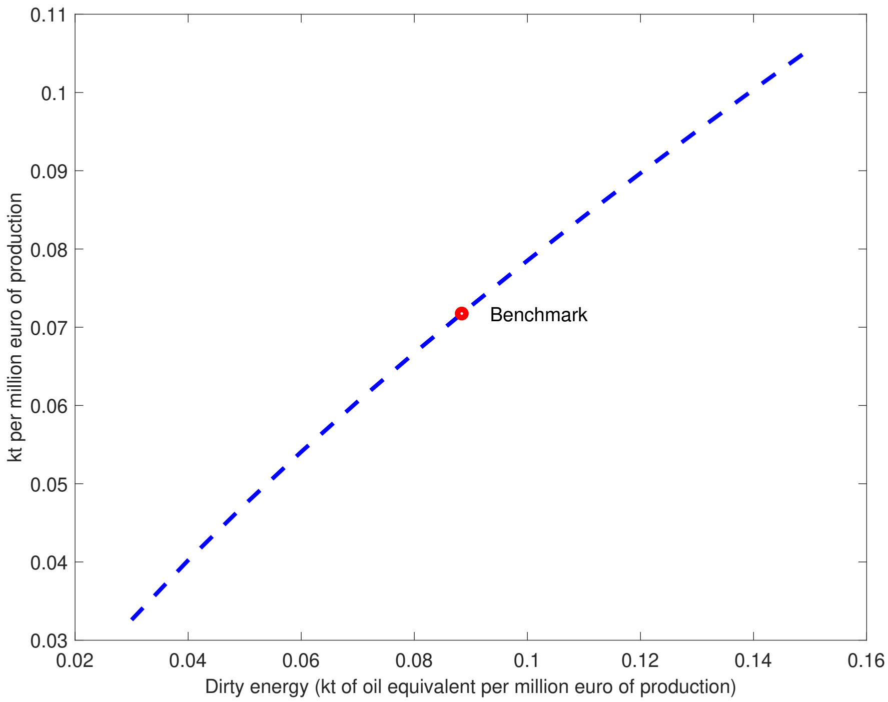


Figure 2: *Emissions as a funtion of dirty energy production*

tainty surrounding these and other energy and environmental parameters, we conduct a sensitivity analysis at the end of the Results 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 GDP growth and emissions between 2010 and 2050, assuming no policy intervention. To achieve this, we calibrate the growth rate of certain exogenous technological variables by referencing the observed changes in GDP, in carbon emissions, and in the ratio of green to brown energy production from 2010 to 2019.

4..1 Baseline scenario: 2010-2019

Between 2010 and 2019, Spain's real GDP grew by 10.6%, while carbon emissions decreased by 11.8% and the ratio of green energy to brown energy production increased

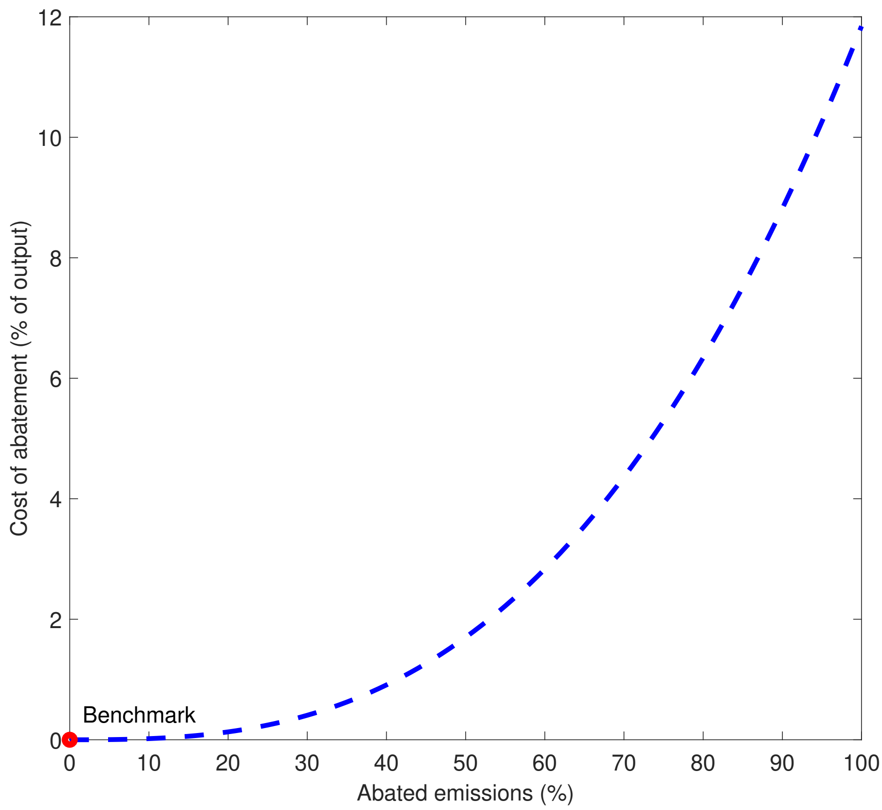


Figure 3: *Abatement costs as a function of the abatement share of emissions*

by 14.5%. We attribute these changes to different types of technological progress, specifically, technological progress that augments total factor productivity ($g_{\widetilde{A}}$), technological progress biased towards green energy production (g_{ς^g}), and technological progress that augments emission efficiency ($g_{\gamma_1^b}$).

It is worth noting 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 account for other regulatory mitigation policies implemented between 2010 and 2019.

Under the assumption that technological progress is unknown by economic agents, we introduce unanticipated series for $\widetilde{A}t$, ς_t^g, and γ_{1t}^b over a ten-period span from 2010 to 2019. Each series has a different constant growth rate, and these growth rates are calibrated such that when the three unanticipated series, starting from their initial calibrated values $\widetilde{A}0$, ς_0^g, and γ_{10}^b, are included together in the model, the dynamic solution matches

	Model	Data	Emissions reduction
TFP growth ($g_{\tilde{A}}$)	1.56	–	-0.2
Green bias tech progress (g_{ς^g})	1.21	–	-0.4
Emissions efficiency ($g_{\gamma_1^b}$)	1.08	–	-1.2
GDP growth	1.13	1.13	–
Carbon emissions reduction	-1.39	-1.39	–
Relative increase in green energy production	1.52	1.52	–

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

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 decline in emissions, and the rise in the ratio of green to brown energy production during the period are consistent with an annual growth rate of 1.56% for TFP, 1.26% for green energy bias technology, and 1.56% for emissions efficiency. When the model incorporates all three sources of technological progress, it is able to generate the annual average growth rates in GDP, emissions, and the ratio of green to brown energy production. Notably, the technological progress that increases the efficiency of emissions makes the largest individual contribution to the decline in emissions.

Figure 4 provides an overview of how the model captures the decline in emissions per unit of GDP when considering all three types of technological progress. However, the model fails to replicate this decline if any of these types of progress is omitted.

4..2 Baseline scenario: 2019-2050

We feed the model year to year with the calibrated growth rates from Table 1 to project the emissions from 2019 to 2050, starting with the observed data in 2019. Figure 5a illustrates the baseline scenario along with two alternative scenarios. In the optimistic scenario, we increase by one-third the growth rates of the exogenous TFP, green bias technology progress, and emissions efficiency. Conversely, in the pessimistic scenario, we reduce by one-third these growth rates.

To set the emissions target we take into account that our carbon decay rate, $1-\eta$, which can be interpreted as the rate of natural Earth absorption of carbon stock, implies that natural carbon sinks capture about 30% of global emissions, coinciding with

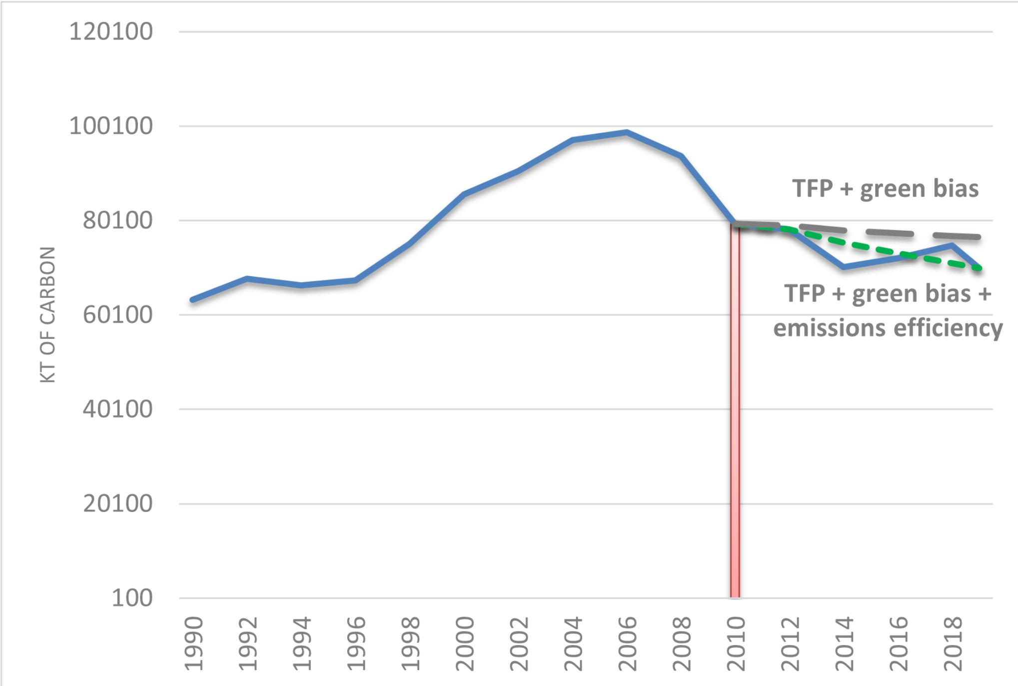


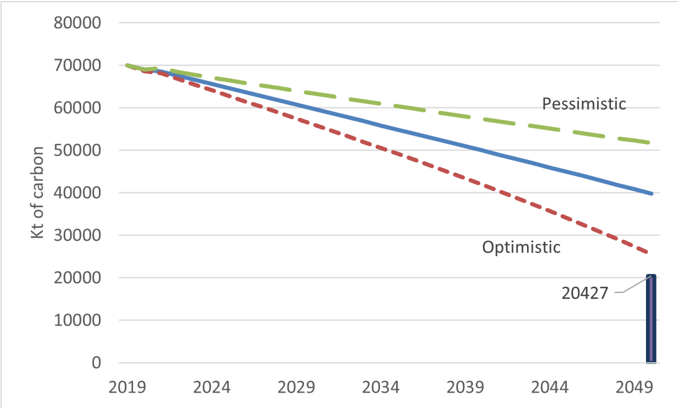
Figure 4: *Observed and projected evolution of emissions, comparing the actual trend since 2010 to a model scenario with TFP growth and decarbonization. Source: IEA-EDGAR (2022) and own analysis*

most of the estimates [9]. Extrapolating to Spain, we assume that reducing overall emissions by about 70% of the 2021 emissions is required to fulfill the Paris Agreement's goal of net-zero greenhouse gas emissions by 2050. Taking into account the Spanish carbon emissions in 2021 under the baseline scenario, we set an emission target of 20,427 kt of carbon.

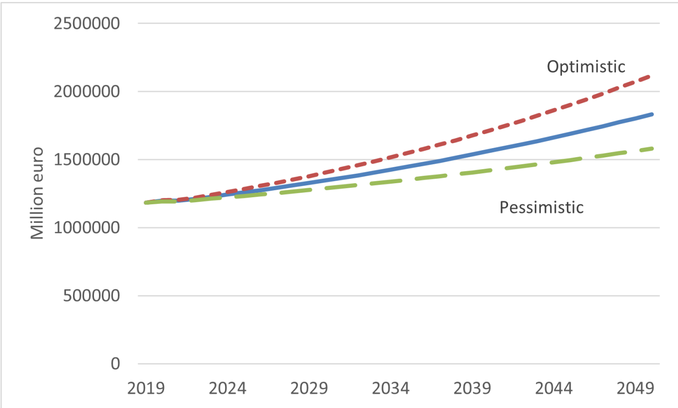
Table 2 shows the percentage reduction in emissions from 2019 to 2050 attributed solely to the expected behavior of the technology under each of the three scenarios, along with the additional effort required beyond the projected 2050 values to meet the target. In the baseline scenario, the anticipated technological advancements between 2019 and 2050 are projected to achieve a 43.2% reduction in emissions compared to 2019 levels, representing more than half of the total mitigation effort needed by 2050.

This projection of emissions goes hand in hand with the consequent projections of all the macroeconomic, energy, and environmental variables in the model. Figure 5b illustrates the evolution of GDP for the three scenarios considered. In the baseline scenario

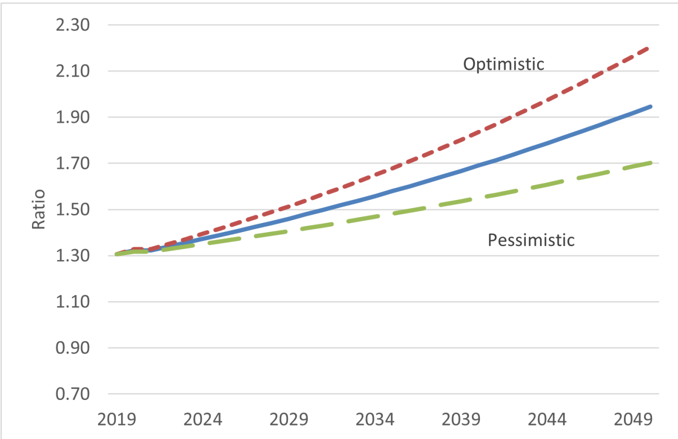
[9] See Brienen *et al*. (2020)



(a) *Projected carbon emissions*



(b) *Projected GDP*



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

Figure 5: *Baseline, optimistic and pessimistic scenarios 2019-2050*

	Pesssimistic	Baseline	Optimistic
Reduction wrt 2019	-26.1	-43.2	-63.4
Reduction for target	-60.5	-48.6	-20.1

Table 2: *Emissions reduction in 2050 with respect to 2019 and required reduction to achieve the emissions target (percentage)*

	Commodity price	Green investment	Emissions taxes	Taxes + Subsidies
Emissions	-23.14	-16.87	-29.44	-28.11
GDP	-0.75	1.44	-0.31	0.56
Consumption	-1.02	-0.57	0.04	0.02
Green energy production	5.43	43.56	4.53	25.08
Brown energy production	-31.70	-23.11	-24.10	-25.48
Energy mix distribution	-13.53	9.52	-9.29	0.07
Green energy price	7.75	-17.10	3.86	-6.32
Brown energy price	17.18	-0.18	2.74	-2.94
Energy mix price	12.57	-8.46	6.31	-1.28
Abatement	0.00	0.00	13.03	10.85

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

GDP grows at an average rate of 1.4% (1.9% in the optimistic and 0.9% in the pessimistic scenario). Figure 5c illustrates the increase in the ratio of green to brown energy production driven by technological advancements. By 2050, this ratio is projected to rise from 1.3 in 2019 to nearly 2 in 2050.

4..3 Mitigation plans

The Paris Agreement requests each country to design its post-2020 climate actions, known as their Nationally Determined Contribution (NDCs). We investigate here the economic impacts of various mitigation strategies designed to bridge the emissions gap in 2050 between projected levels of emissions and the maximum allowed under the Paris Agreement. In order to achieve this, we compare the expected evolution of relevant variables from 2019 to 2050 with and without the implementation of these plans. This enables us to evaluate the transitional effects of the policy within the specified period. We consider these plans to be initially unanticipated, but once they begin implementation, agents become aware of how they will evolve over time.

	Commodity price	Green investment	Emissions taxes	Taxes + Subsidies
2019-2050				
Baseline	-1.10	-0.92	0.17	0.01
Optimistic	-0.46	-0.38	0.03	0.01
Pessimistic	-1.37	-1.15	0.32	-0.03
Long run				
Baseline	-4.92	8.62	-3.38	-1.49
Optimistic	-2.04	3.57	-1.02	-0.10
Pessimistic	-6.12	10.73	-4.63	-2.47

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

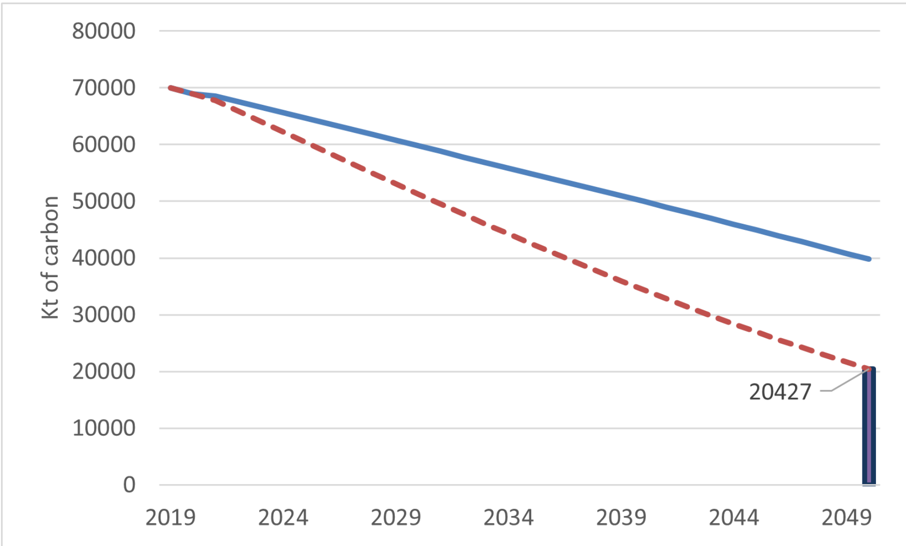
4..3.1 Increase in the price of imported commodity

Brown energy relies on an imported commodity, represented by m_t^b (such as oil or gas), to produce. The price of this commodity, $P_t^{m^b}$, is determined in international markets and is considered exogenous for Spain. In addition, the government can apply a tariff on imports of this commodity.

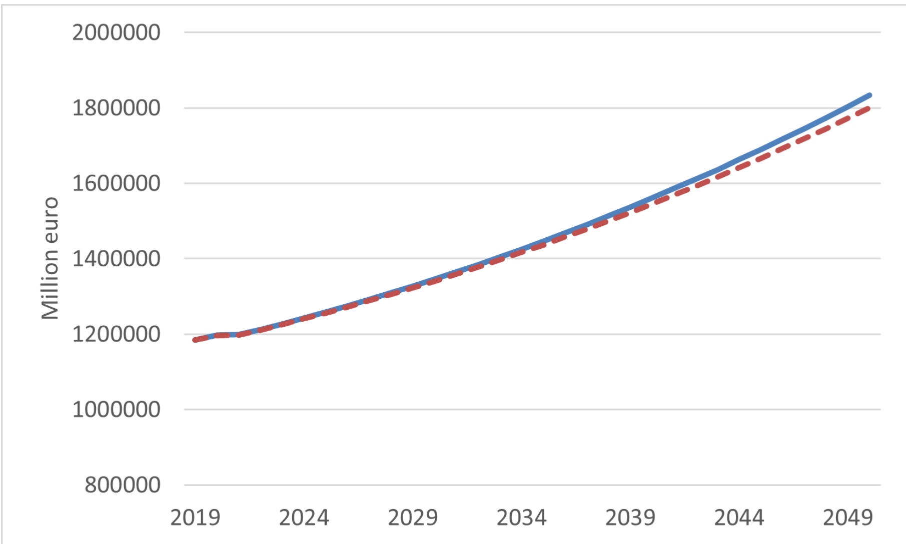
The first strategy we study is related to the price of the imported commodity used to produce energy. We assume that a fiscal authority announces a fiscal strategy of progressively increasing the relative price of the commodity in a linear manner until 2050, at which point the relative price will stabilize at an upper bound. 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 results, the commodity price (relative to the consumer price index) required to achieve the emissions objective will progressively increase by 80% by 2050 compared to 2019. Figure 6a depicts the anticipated emissions reduction resulting from the fiscal strategy of gradually raising the relative price of imported commodities. Conversely, Figure 6b illustrates the deviation of the baseline GDP trajectory caused by this particular strategy.

We can calculate the percentage difference between the area under the continuous blue lines and the red dashed lines over the considered period. Table 3 presents these calculations in the first column for a broader range of variables. The variation in accumulated values can be found in the first column of Table 3. This strategy reduces brown energy production by 32%, increases green energy production by 5.4%, and raises the cost of the energy mix by 12.6%. The total reduction in emissions over the period amounts to



(a) *Carbon emissions*



(b) *GDP*

Figure 6: *Evolution of carbon emissions and GDP. Baseline and increase in commodity prices*

23.14%, while the cumulative loss of GDP is estimated to be only 0.75 percentage points.

Figure 7 shows the percentage deviations of a selection of variables from the baseline over every year of the 32-year period considered. 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 percentage reduction in consumption that would leave households equally well-off before and after the change in the policy. For the sake of clarity, we have changed the signs in this subplot, with a negative sign indicating a reduction in welfare.

This strategy involves a substantial substitution of brown energy for green energy and results in a higher price for the energy mix. However, the overall macroeconomic impact is relatively limited, particularly compared to that of a degrowth strategy. By 2050, GDP is projected to be 1.8% lower than in the baseline scenario, and consumption is expected to be 2.1% lower.

Table 4 compares different measures of welfare changes for various mitigation plans in terms of equivalent consumption. The first section of the table presents the average percentage change in welfare between 2019 and 2050, while the second section illustrates the steady-state long-run outcomes. We distinguish between the baseline, optimistic, and pessimistic scenarios. The results in the first column show a moderate accumulated reduction in welfare (-1.1%) for the baseline scenario during the period 2019-2050, which widens to almost -5% in the long run. In the pessimistic scenario, the long-run welfare loss is projected to be around -6% (-2% in the optimistic scenario)

4..3.2 Subsidies to green investment

The model assumes that subsidies to green investment are represented by the exogenous variable t_t^{ig}. Now these subsidies increase linearly over time from an initial value of zero until the target emissions are reached in 2050, at which point they remain constant. In the baseline scenario, the subsidy amounts to 3.5 times the cost of investment in 2050, and the cost to the government budget is 2.5 percentage points of GDP in that year. This cost is financed by a lump-sum tax in the model economy. Figures 8a and 8b illustrate the projected paths for emissions and GDP, respectively.

Contrary to the previous plan, a dynamic scheme of subsidies to green investment favors GDP growth, which in 2050 is 3.6% higher than in the baseline scenario, as shown in Figure 9. Green energy production will increase by 130% by 2050 compared to 2019, while brown energy will decrease by 67%. The price of green energy experiences a pronounced drop of more than 50%, and due to higher taxes, welfare moderately decreases for 16 years before recovering afterward.

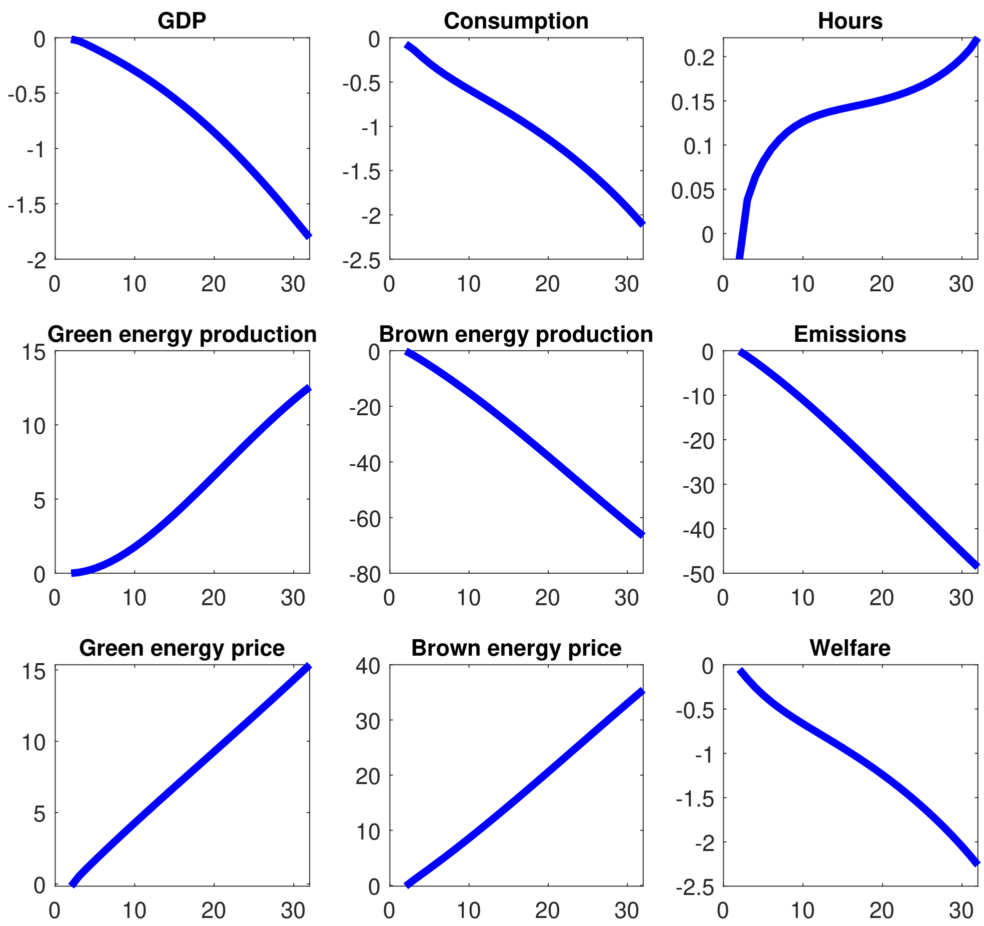
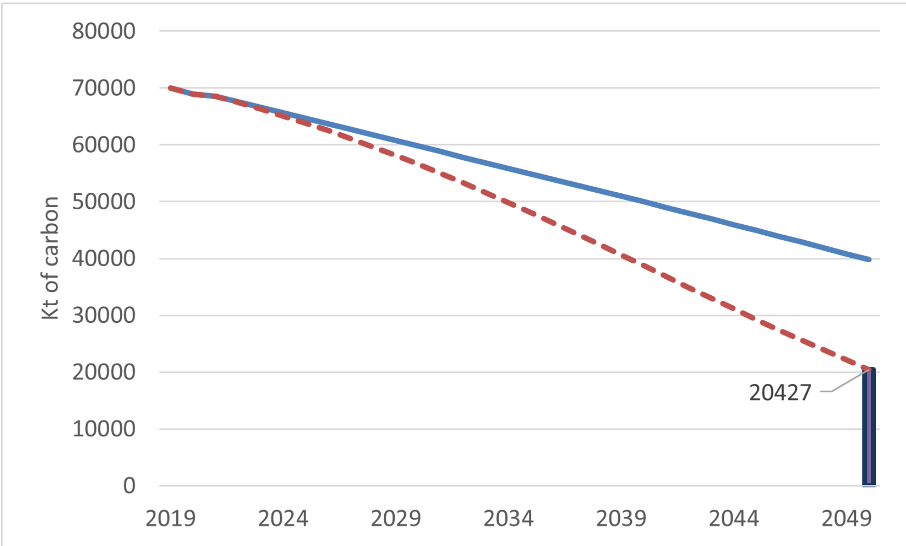
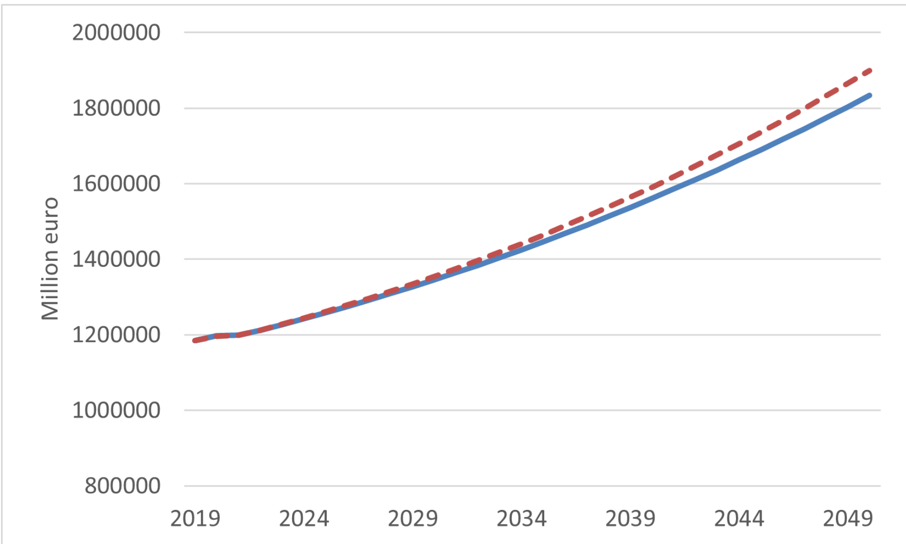


Figure 7: *Dynamic macroeconomic effects of a continuous increase in the commodity prices (percentage deviations with respect to the baseline period)*

Table 3 reflects that during the period, the economy experiences an increase in energy consumption of over 9%, primarily driven by the higher demand for green energy, which is non-polluting. In contrast, the use of brown energy decreases significantly. Overall, the average reduction in emissions over the period is approximately 17%. However, this strategy does not lead to a reduction in energy intensity. While the energy intensity of the economy increases, accumulated welfare decreases slightly by less than 1% in terms of consumption during the projected period, primarily due to higher taxes. However, welfare in the long run increases by 8.6% (Table 4), thanks to the higher level of capital in the economy.



(a) *Carbon emissions*



(b) *GDP*

Figure 8: *Evolution of carbon emissions and GDP. Baseline and subsidies in green investment*

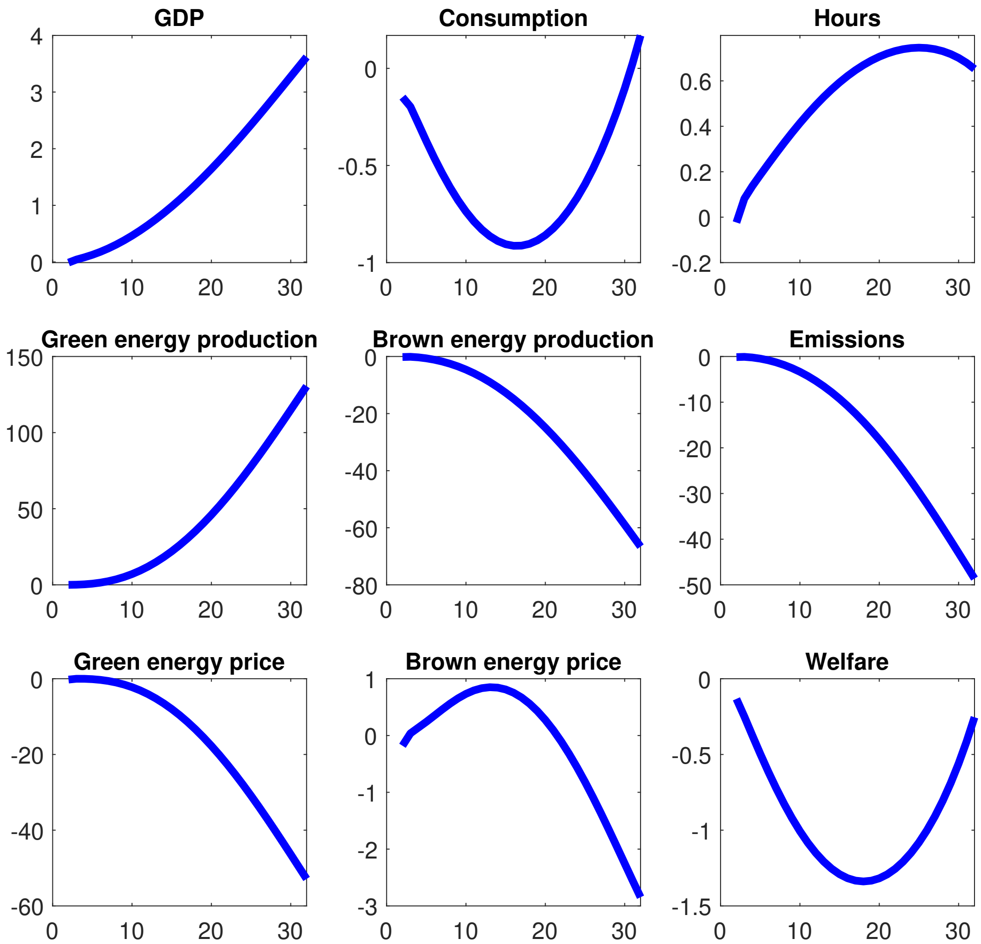
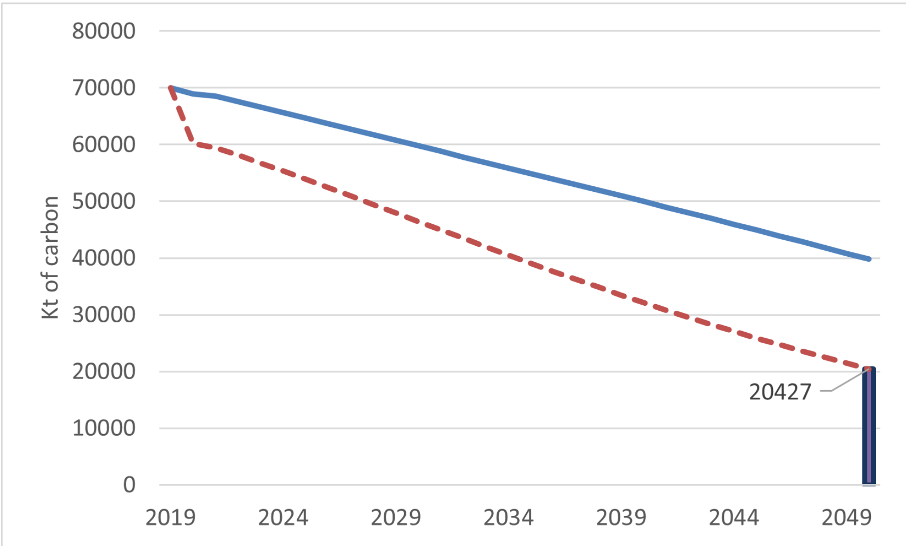


Figure 9: *Dynamic macroeconomic effects of a continuous increase in the subsidy to green investment (percentage deviations with respect to the baseline period)*

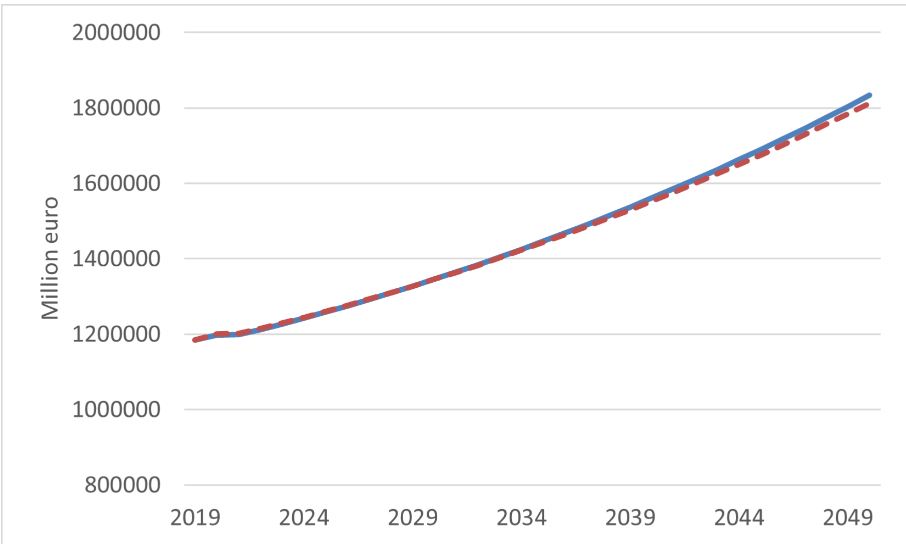
4..3.3 Emission taxes

In this exercise, we assume that emissions taxes, denoted by τ_t, have been zero up to the year 2019. Starting from 2019, we increase these taxes linearly over the next 31 years in order to reach the emissions target by 2050. From that year onward, the tax rate remains constant.

We obtain that increasing this tax in the coming years by €61 per tonne of CO2 (2010 prices) will fulfill the target in the baseline scenario (the upper limit of the tax would be 17 euros in the optimistic scenario and 89 euros in the pessimistic one). These figures



(a) *Carbon emissions*



(b) *GDP*

Figure 10: *Evolution of carbon emissions and GDP. Baseline and emission taxes*

are something lower than others that have appeared in the literature. For instance, for Dietz and Stern (2015) taxes would move in the range \$32-103/tCO2 (2012 prices) in 2015, increasing to \$82-260/tCO2 in two decades. For CE Delft (2010), based on an informal meta-analysis of various studies, the values of CO2 taxes would be as low as €20/tCO2 and as high as €180/tCO2 in 2050 (2012 prices). OECD (2021) employs three carbon price benchmarks ranging from €30/tCO2 to €120/tCO2. According to the High-Level Commission on Carbon Pricing (2017) the price signals that will decarbonize electricity generation and heavy industry through the medium term (2030) would be in a range between 30US\$/tCO2 and 100US\$/tCO2.

Figure 10 shows the path for emissions and GDP in relation to the baseline scenario, while Figure 11 represents the year-to-year percentage deviation of a set of variables with respect to the baseline. By 2050 GDP will decrease 1.2% with respect to the projected value in the baseline, dirty energy falls by 45%, and green energy increases by 10%.

Table 3 presents the average macroeconomic effects of the emission taxing plan from 2019 to 2050. The plan has a minimal impact on overall GDP, resulting in only a 0.3% cumulative decrease. There is virtually no impact on aggregate consumption. Notably, firms respond to the increased taxes by investing in abatement measures that would account for a 13% reduction in accumulated emissions during the period.

Welfare remains unaltered on average during the period 2019-2050 (Table 4). In the long run, however, welfare decreases in the steady state equivalent to 3.4% of the initial consumption (1% in the optimistic scenario and 4.6% in the pessimistic one). Comparing the welfare effects of different plans, it appears that emission taxes would be the least harmful until the emission target is achieved. Subsidies on green investment, on the other hand, would be the most beneficial for welfare in the long run.

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.

Once again, we assume a linear increase in taxes until the emission target is reached in 2050. The emission tax increases to €48, as opposed to €61 in the lump-sum case.[10]

[10] According to Stock and Stuart (2021), a carbon tax as low as \$20 per ton of CO2, when combined with investment tax credits, would be sufficient to achieve an 80% reduction in power emissions.

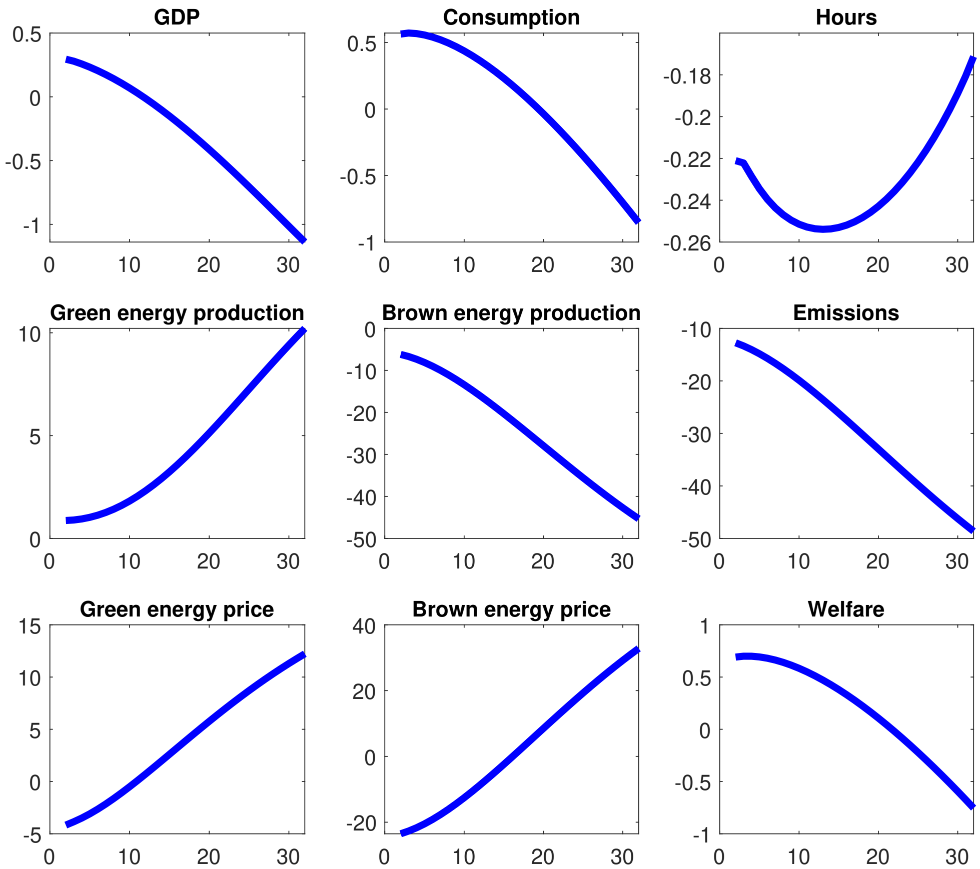
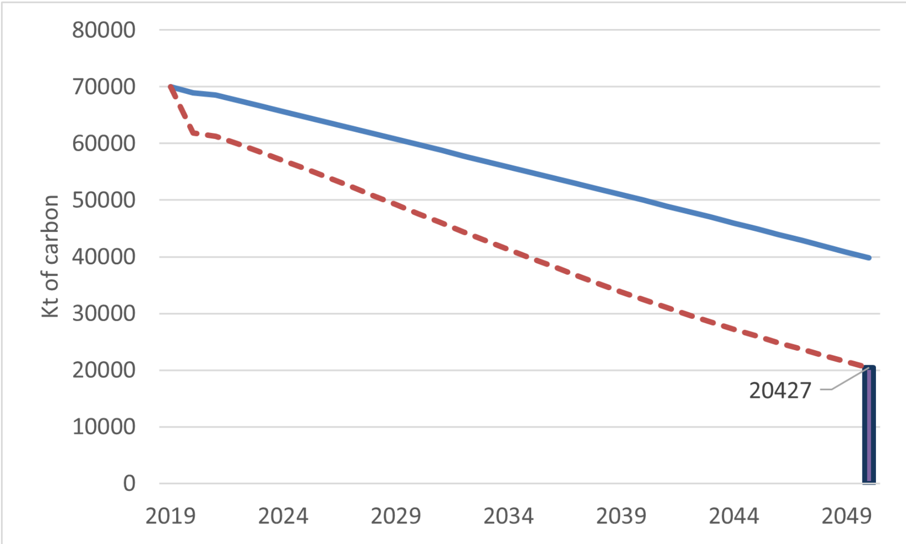


Figure 11: *Dynamic macroeconomic effects of a continuos increase in the tax to emissions (percentage deviations with respect to the baseline period)*

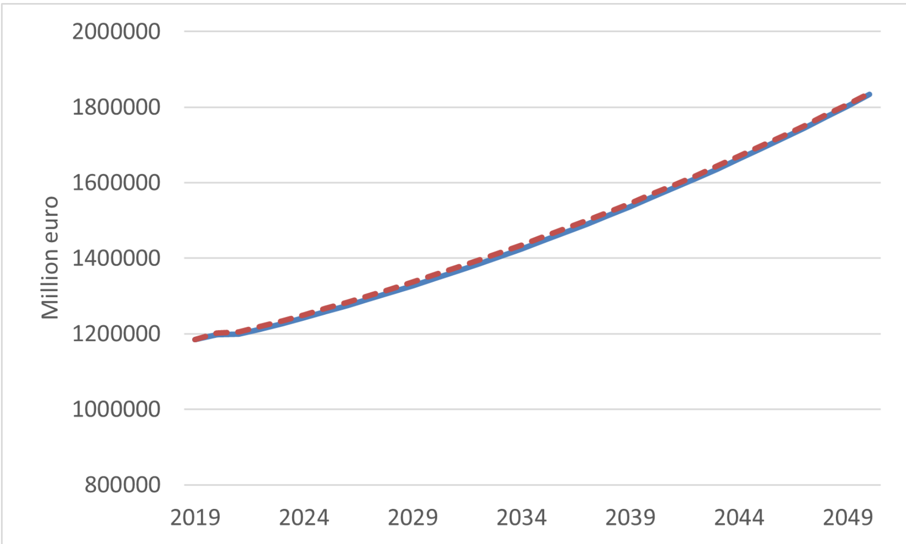
This measure has a small positive impact on accumulated GDP during the transition period, as illustrated in Figures 12 and 13.

The final column in Table 3 demonstrates that this policy leads to an almost perfect substitution between brown and green energy, leaving the energy intensity unchanged.

According to Table 4, this strategy avoids the short-term welfare cost associated with financing green investment through taxes and reduces the long-term welfare cost by more than half compared to returning carbon tax revenues through household transfers.



(a) *Carbon emissions*



(b) *GDP*

Figure 12: *Evolution of carbon emissions and GDP. Baseline and emission taxes used to subsidize green investment*

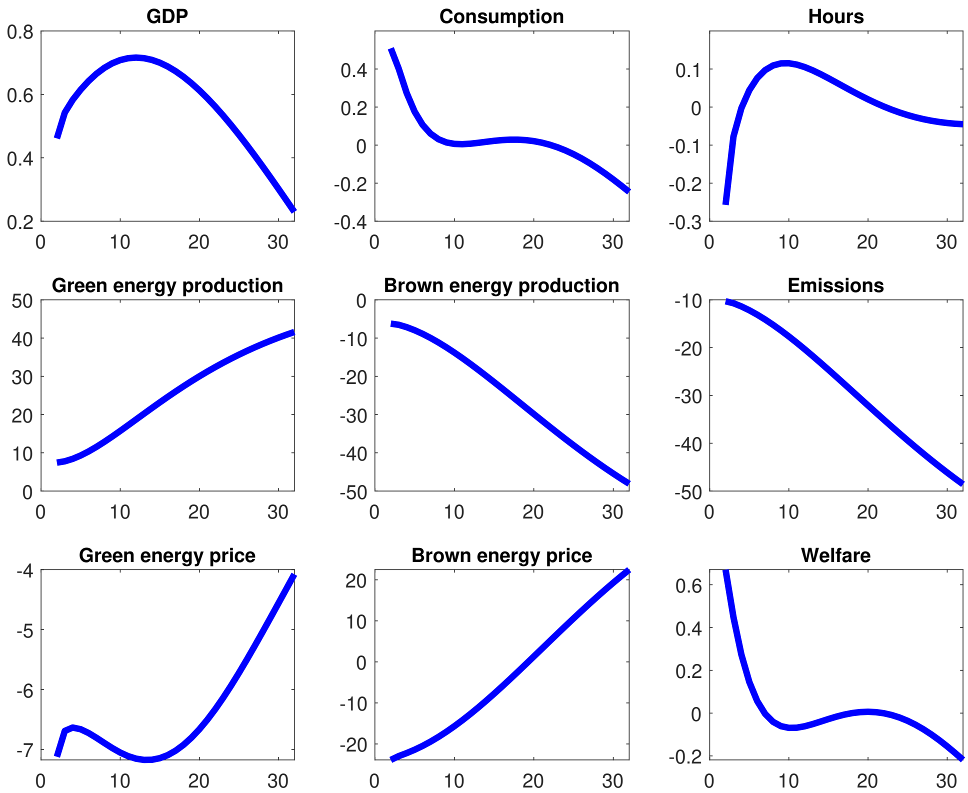


Figure 13: *Dynamic macroeconomic effects of a continuos increase in the tax to emissions used to subsidize green investment (percentage deviations with respect to the baseline period)*

4..4 Cap-and-trade: sensitivity analysis

Our focus in this section is on a cap-and-trade program. We assume that the government imposes an exogenous linear path of emissions reduction until reaching the emissions target in 2050, and maintains emissions at the target level thereafter. Consequently, the trajectory of carbon prices becomes endogenous to align with the specified emission path.

Using this program, we will analyze the robustness of our results by examining the effects of various environmental factors within the model.

Figure 14 represents the dynamic path for emission reductions and carbon prices corresponding to the baseline scenario under perfect foresight. Prices peak in 2050 (vertical line) at a level of 64.4€/tCO2, slightly higher than the tax the model delivers in the tax on emissions policy.

Table 5 represents the results of the robustness analysis. In all cases considered, the

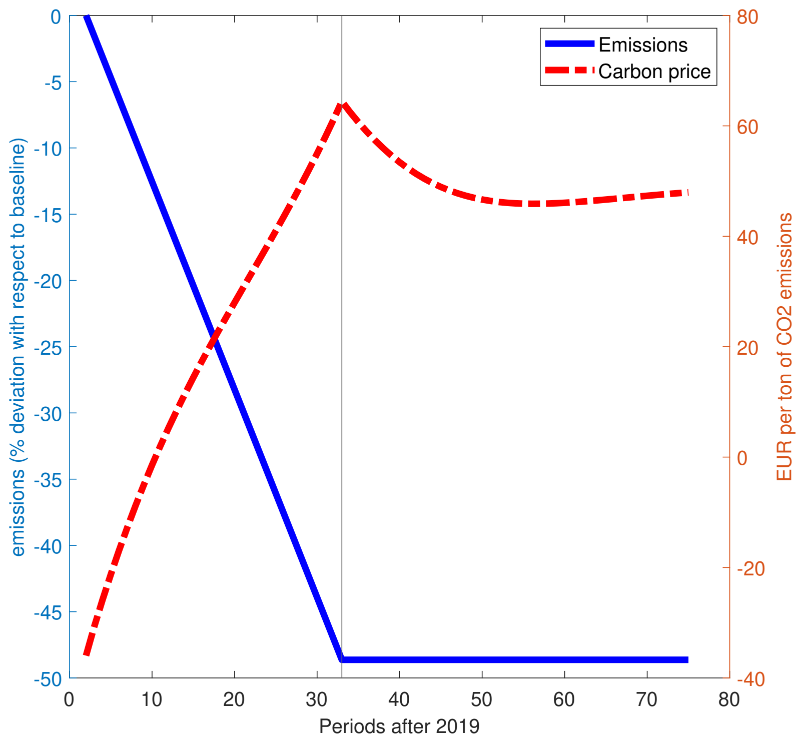


Figure 14: *Exogenous reduction path in emissions and endogenous carbon price reaction*

projected path for emissions remains the same. First, we assume a systematic coordinated strategy where the rest of the world reduces emissions at the same pace as Spain, such that the ratio $\frac{e_t}{e_t^{row}}$ remains constant over time. This approach does not affect the carbon price by 2050, but it increases welfare with respect to the baseline by approximately 0.5pp during the transition period and 1.1pp in the long run. This is because of the more pronounced reduction in the atmospheric carbon stock.

Then, we consider the case where it becomes more difficult to switch from dirty energy to clean energy by reducing the elasticity of substitution between brown and green energy from the benchmark of $\sigma^x = 3.94$ to $\sigma^x = 1.97$. This change results in an increase in the carbon price to €84.3/tCO2 by 2050, which reduces welfare in the long run by 0.5pp compared to the baseline.

When firms face a lower elasticity of costs (z_t^b) to the share of abated emissions (μ_t^b), the costs of abatement for the firms can increase or decrease depending on the initial value of μ_t^b. For low values of μ_t^b, a fall in θ_2^b increases (z_t^b) for the same change in μ_t^b. In the table, we have halved the value of θ_2^b from the benchmark of 2.8 to 1.4. The carbon

	Welfare		Carbon price
	2019-2050	Long run	by 2050 €/tCO2
Baseline	0.2	-2.7	64.4
Coordination	0.7	-1.6	64.9
Halving σ^x	0.3	-3.3	84.3
Halving θ_2^b	0.1	-3.6	81.1
Halving d_1, d_2	0.2	-2.7	64.9
Increasing γ_1^b by 50%	-0.1	-2.6	62.9
Increasing A^x by 25%	0.2	-2.7	66.3
No technological progress	0.5	-4.6	126.1

Table 5: *Change in welfare and carbon pricing to different environmental settings*

price increases to 81.1 €/tCO2 by 2050, almost 17 € more than in the baseline. Welfare, in the long run, falls by an additional 0.9pp.

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 50% lower than the one considered so far. Basically, we divide both d_1 and d_2 by 1.5. This change does not affects the carbon price or welfare, as production is less harmful to productivity both before and after carbon pricing.

We also increase the marginal effect of dirty energy production on emissions by 50% by changing the parameter γ_1^b. As shown in Equation 12, this change makes a rise in carbon price more effective in inducing abatement because more polluting brown energy production becomes relatively more expensive with higher taxes. Thus, pricing carbon also prompts a stronger response to substitute dirty energy for cleaner energy. Table 5 shows that in this economy, the carbon price increases slightly less than in the baseline. However, it does not affect significantly welfare effects.

When we assume a higher efficiency of energy distribution, such as the initial A_t^x is 5% higher, the results remain virtually unchanged.

Finally, to assess the significance of technology, we examine a scenario where there is no technological progress between 2019 and 2050. In this case, carbon prices alone must achieve the objective of a 70% emission reduction by 2050. The carbon price will rise to €126, resulting in a negative impact on long-term welfare of almost 5%.

4..5 Degrowth

Degrowth is used in discussions related to sustainable development and environmentalism. It refers to the idea of shifting away from traditional economic growth by down-scaling global consumption and production.[11] We implement this plan by assuming that consumers reduce progressively in a linear way their preferences for consumption and augment their preferences for leisure until they observe the strategy has succeeded in terms of emissions by 2050, where they stabilize preferences since then. To that end, we introduce a shifter in the utility function, ς_t^c, whose evolution over time is perfectly planned by consumers. The higher ς_t^c the less households value consumption and the more they value spare time:

$$\left((1-\varsigma_t^c)\frac{c_t^{1-\sigma}}{1-\sigma} - (1+f_c\varsigma_t^c)\kappa_L\frac{h_t^{1+\varphi}}{1+\varphi}\right) \tag{35}$$

where f_c is a parameter that accounts for the significant difference between the weight of consumption and leisure in the utility function, and prompts households to substantially reduce both their consumption and increase their leisure time in response to changes in ς_t^c

This strategy implies an unbearable cost in terms of consumption and GDP, with reductions of 73.6% and 55.2% respectively (Table 6). On the positive side, dirty energy production falls by 49.8% consequence of an overall shrink in the total energy of 26.2%.

Figure 15 shows the percentage deviations of a selection of variables from the baseline over every year of the 32-year period considered. The last two subplots in the figure display the welfare dynamics in terms of the percentage consumption required to compensate for the loss in utility. Specifically, they show the percentage reduction in consumption that would leave households equally well-off before and after the change in preferences. For the sake of clarity, we have changed the signs in these subplots, with a negative sign indicating a reduction in welfare.

The first subplot in welfare analysis, 'Welfare enforcement,' assumes that changes in consumption and leisure are evaluated using a utility function with the same preferences as households had before the change. This can be interpreted as if the projected reduction in consumption and working hours were not due to optimal household decisions but rather an imposition by authorities. In contrast, the second case, referred to as 'Welfare voluntary,' compares utility based on changing preferences. In this case, people value less consumption and more leisure time, leading to an improvement in well-being for

[11] See Demaria *et al.* (2013). Also, in May 2023, the European Parliament hosted the conference "From growth to 'beyond growth': Concepts and challenges" to explore alternative economic narratives that go beyond traditional notions of growth. The conference aimed to foster discussions on achieving a systemic shift and fundamental transformation, which may include the concept of degrowth (Evroux, Spinaci and Widuto, 2023)

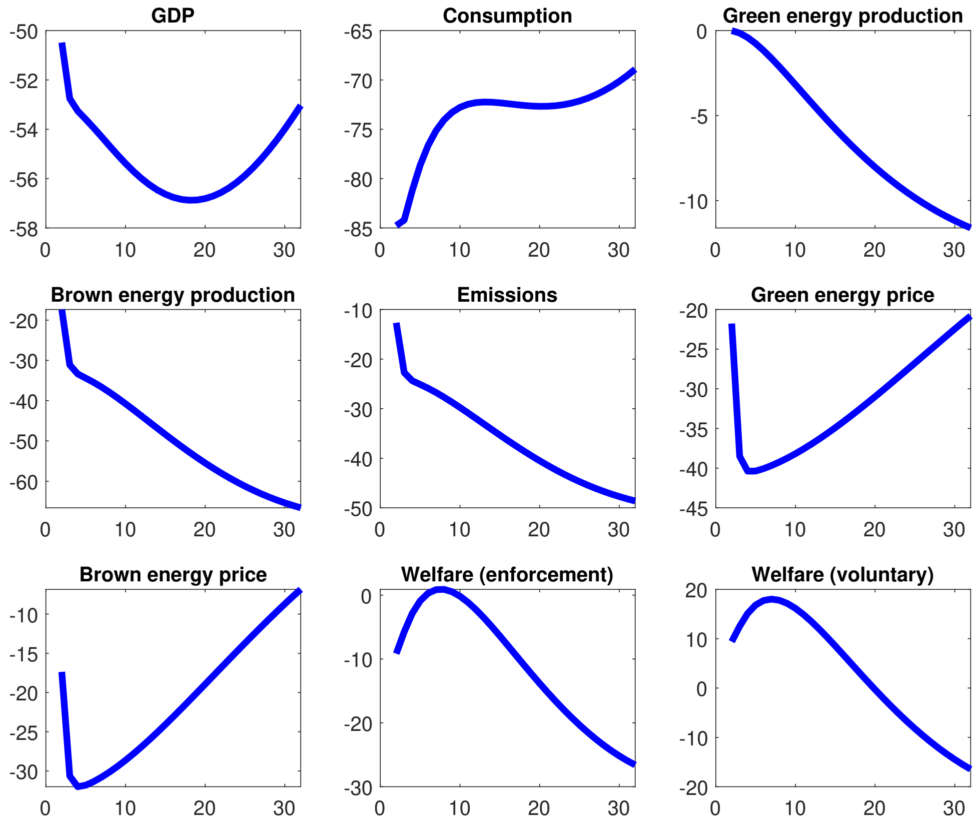


Figure 15: *Dynamic macroeconomic effects of a degrowth strategy (percentage deviations with respect to the baseline period)*

over 15 years as the value of consumption decreases and desired leisure increases.

According to Table 7, during the study period, average welfare falls on average by 11.2% (consumption equivalent) in the baseline scenario under enforcement, but it increases by 3.1% under voluntary restraint of consumption and working time. However, in the long run, the reduction in welfare is significant under both enforcement and voluntary assumptions (-40.2% and -30.3% of equivalent consumption, respectively).

	Degrowth
Emissions	-36.35
GDP	-55.19
Consumption	-73.59
Green energy production	-6.25
Brown energy production	-49.80
Energy mix distribution	-28.49
Green energy price	-31.83
Brown energy price	-20.78
Energy mix price	-26.19
Abatement	0.00

Table 6: *Macroeconomic effects during the period 2019-2050 of a degrowth strategy, expressed as percentage deviations from baseline paths*

	Welfare	
	Enforcement	Voluntary
2019-2050		
Baseline	-11.20	3.15
Optimistic	-9.86	0.19
Pessimistic	-11.76	4.38
Long run		
Baseline	-40.18	-30.32
Optimistic	-4.05	-3.07
Pessimistic	-55.22	-41.67

Table 7: *Welfare effects of a degrowth strategy from 2019-2050 and in the long run, expressed as percentage changes in equivalent consumption (negative values = loss, positive values = gain)*

5. Conclusions

The Paris Agreement calls on each country to design its post-2020 climate actions, known as Nationally Determined Contributions (NDCs). Governments have a range of strategies to design their NDCs to mitigate carbon emissions and the final decision on which strategy or combination of strategies to employ should be based on the expected macroeconomic effects and their impact on well-being. Technological progress that lowers the cost of clean energy production and reduces emissions from traditional energy production methods must also play a fundamental role in this decarbonization process.

In this study, we utilized a dynamic general equilibrium model that accounts for key factors related to emissions reduction policies and advancements in technology. Specifically, we considered that the energy used in the production of goods and services can be derived from clean (green) or dirty (brown) technologies. There are various ways in which technological progress can decrease the cost of clean energy in comparison to dirty energy, minimize emissions in dirty energy production, enhance energy distribution efficiency, or decrease the use of production factors and energy per unit of output. Moreover, governments can employ proactive measures to mitigate greenhouse gas emissions, such as offering subsidies for investing in clean energy, setting targets for the growth of commodity prices (e.g., gas, oil), implementing an emissions tax, or encouraging cap-and-trade programs.

With this model, we have developed a central scenario for the evolution of emissions that takes into account the various types of technological progress and is consistent with the observed changes in emissions between 2010 and 2019, as well as the general equilibrium solution of the model. From this baseline scenario, we have also created an optimistic scenario, where technological progress toward decarbonization accelerates, and a pessimistic scenario, where technological progress slows down. The importance of keeping up with recent emission-saving technological progress or accelerating it is evident, as our baseline scenario implies achieving half of the emissions reduction goal by 2050. Using these scenarios, we can estimate the effort required to achieve the target of net-zero emissions by 2050 under different mitigation strategies, and obtain the consequences for well-being.

For a plan based on increasing the price of imported commodities for brown energy production, our research suggests that the price should increase by 80% by 2050. In the case of a subsidy for green energy investment, our central scenario indicates that the subsidy would need to provide a return of 3.5 times the cost of investment in 2050. This would come with a budgetary cost to the government of 2.5 percentage points of GDP in that year. For a tax on emissions, our findings suggest that taxes should increase by 61 euros per tonne of CO2 (at 2010 prices) from today to 2050. In a cap-and-trade program, the price of emissions would rise until it reaches 64 euros per tonne of CO2.

When we compare the changes in welfare associated with these three strategies, we distinguish between the transition period (2019-2050) and the long term (after 2050, when the reduction in emissions has stabilized). Our results suggest that, in the central scenario, the strategy based on increasing taxes on emissions involves the lowest cost in terms of welfare along the transition path. In fact, welfare remains virtually unchanged, or if anything, increases slightly, which is a consequence of the fact that consumption increases during the first half of the adjustment period due to expectations of higher taxes in the future, and the fact that as aggregate investment decreases, resources are released that are used for consumption of goods and services. In any case, our model produces moderate effects on welfare during the transition period for mitigation plans based on different fiscal policy instruments, ranging from a 0.32 welfare gain (in terms of equivalent consumption) for emissions taxes to a 1.37% welfare loss for the increase in the price of the imported commodity, in the most pessimistic scenario about the evolution of technology.

The differences in welfare derived from the different plans are more evident in the long run. When we compare the steady-state effects, subsidies for investment in green energy are unrivaled, resulting in welfare gains of more than 8.5% in the baseline scenario. This is explained by the greater production that can be derived from higher green capital endowments in the future. By contrast, we estimate that emissions taxes or tariffs on gas and oil imports reduce welfare by 3.4% and 4.9%, respectively, in the long run.

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.

At a different level, a strategy based on degrowth, even assuming that it is due to a genuine change in preferences by the population, would increase welfare by 3.5% during the transition period (mainly due to a lower valuation of consumption and a higher valuation of leisure), but would lead to a drastic drop in welfare in the long term, which we simulate could reach 32.3% in terms of equivalent consumption in the baseline scenario.

A coordinated policy in which the rest of the world follows the same path of reducing emissions would improve long-term welfare by 0.9 percentage points. Changes to the configuration of the damage function, abatement cost function, energy mix, or initial efficiency in the use of energy would only moderately affect the welfare implications of reducing emissions on a cap-and-trade scheme.

Our study can be interpreted in a positive way, offering a picture of welfare and other macroeconomic effects of different mitigation plans. A normative analysis with an implied optimal path of government interventions is next on our research agenda.

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Appendix A The complete Model

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

40 equations for 40 variables (definitions not included):

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, t_t, 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	0.4356	Scaling parameter in the emission function
γ_2^b	0.2700	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	39.200	Work disutility
$\bar{\pi}$	1.0000	Inflation rate in the steady state
σ^r	6.2632	Elasticity of substitution in intermediate goods
κ_p	3.8729	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	0.9879	Natural absorption of athmospheric carbon
d_0	0.0014	Parameter in the damage function
d_1	$-7.1454e-06$	Parameter in the damage function
d_2	$1.6798e-08$	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

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	–