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J. ANDRÉS
J.E. BOSCÁ
R. DOMÉNECH
J. FERRI

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J. Andrés[a], J.E. Boscá[a,b], R. Doménech[a,c] and J. Ferri[a,b]

a University of Valencia, Spain
b Fedea, Spain
c BBVA Research, Spain

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Abstract

We evaluate the welfare and macroeconomic implications of three distinct strategies aimed at reducing carbon emissions, which could be categorized within the diverse landscape of ideas encompassed by the degrowth literature. These strategies include penalizing fossil fuel demand, substituting aggregate consumption with leisure, and curbing consumption by limiting total factor productivity growth. Using an environmental dynamic general equilibrium model (eDGE) that incorporates both green renewable technologies and fossil fuels in the production process, our study sets an emissions reduction target aligned with the goals of the Paris Agreement by 2050. The results reveal that the strategies analyzed, which most closely align with the strictest interpretations of degrowth—namely, a reduction in the consumption of goods and services compensated by an increase in leisure, or strong impediments against conventional economic growth—may entail significant economic consequences, leading to a notable decline in welfare. In particular, a degrowth scenario aimed at curbing consumption through a decline in Total Factor Productivity (TFP) yields the most pronounced reduction in welfare. Conversely, inducing a reduction in fossil fuel demand by increasing the price of fossil fuels through taxes, despite potential social backlash, shows noticeably less detrimental effects on welfare compared to other degrowth policies. Furthermore, under this degrowth strategy, our findings suggest that a globally coordinated strategy could result in long-term welfare gain.

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

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1. Introduction

There is a far-reaching debate in the literature (see, for example, van den Bergh, 2011, Jakob and Edenhofer, 2014, or Warlenius, 2023) about whether green growth is possible, that is, if economies can continue to grow while reducing net emissions to zero, or if economies must shrink to achieve this goal by 2050. The central issue of this debate revolves around the assertion that, to the extent that the positive correlation between current economic growth and increasing environmental harm cannot be severed, society must look for alternative economic objectives other than pure GDP growth. Degrowth is the term commonly used in discussions related to this debate. It refers to the idea of shifting away from traditional economic growth by downscaling global consumption and production.[1]

In the past two decades, various degrowth proposals have emerged with the overarching goal of achieving net-zero emissions to mitigate the impacts of climate change. Some proponents argue that degrowth is not only a viable but also a desirable strategy on social grounds to attain this objective. For instance, Schneider et al. (2010) provide a positive overview of the literature on sustainable degrowth, defining it as the deliberate downscaling of production and consumption, considered essential for enhancing human well-being and ameliorating environmental conditions. In their comprehensive review of this literature, Weiss and Cattaneo (2017) conclude that advocates of degrowth commonly concur that perpetual economic growth is unsustainable due to our planet's limited resources, emphasizing that such a strategy necessitates profound social transformations. More recently, Kallis et al. (2018) suggest that even strategies centered around green growth are improbable to be sustainable in the long run, thereby highlighting the potential for degrowth to become a tangible and beneficial approach.

As highlighted by van den Bergh (2011), degrowth encompasses various interpretations, including GDP degrowth, consumption degrowth, work-time degrowth, radical degrowth (involving changes in ethical values or preferences), and physical degrowth (involving reductions in resource use and polluting emissions). According to Cosme et al. (2017), degrowth proposals typically pursue three primary objectives: reducing environmental impacts by curbing consumption; redistributing income and wealth within and between countries; and transitioning to a less materialistic society. Numerous policy

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[1] 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).

proposals concerning these last two objectives suffer from a lack of precision in their formulation, while others necessitate grassroots bottom-up changes that can be challenging to foster or enforce within democratic societies. Also, while many proponents of the degrowth strategy endorse measures aimed at enhancing the efficiency of production and trade processes to further uncouple economic activity from emissions—such as carbon taxes or subsidies for green technologies - what truly sets them apart from other environmental perspectives is their staunch advocacy for scaling down production as a vital means to substantially reduce emissions. This paper delves into alternative approaches for implementing a degrowth policy, scrutinizing their welfare implications during the transition toward a net-zero-emissions economy.

The implicit hypothesis of the degrowth strategy is that emissions are an increasing function of GDP. Indeed, the correlation between GDP and emissions, both in per capita terms in 2018, for a large sample of 166 countries (which represent most of the world population) depicted in Figure 1 is very high (0.93). Additionally, the elasticity of emissions per capita to GDP per capita was slightly above one (1.14). This, and other related evidence, has prompted some researchers to conclude that reducing GDP or at least GDP growth is a necessary condition of any successful emissions-reducing strategy.

However, such a conclusion is premature for several reasons. First, it overlooks the heterogeneity among countries. For instance, Figure 1 illustrates that countries with comparable emissions per capita exhibit vast differences in GDP per capita; thus, Switzerland's GDP per capita is more than six times that of Ukraine. Conversely, economies with similar GDP per capita exhibit different levels of emissions per capita; China's emissions per capita are nearly eight times that of Sri Lanka, whereas GDP per capita was only 8.7% smaller.

Second, this conclusion fails to consider the evolving dynamics regarding the relationship between emissions and GDP per capita. There are numerous instances of decoupling between increasing GDP and decreasing emissions. Figure 2 provides examples supporting these observations. For example, despite similar GDP per capita levels, Sweden emits only half the emissions of the US. China had previously mirrored the emissions per unit of GDP trend seen in the EU27, but recently, it has initiated a decoupling between growth and emissions, a trend that began in the EU27 around 1980. Sweden serves as an illustrative case of this decoupling since the mid-1970s. By 2018, Sweden's emissions per capita were nearly half the 1970 levels, while GDP per capita had increased 2.2 times. Sweden's emissions per capita in 2018 were equivalent to China's in 2004, but Sweden's GDP per capita was 7.5 times higher. Spain also experienced a similar path of emissions per capita as Sweden and has witnessed a decoupling of GDP growth from emissions over the last two decades.[2]

Third, and most importantly, simple correlations hide the role of numerous factors that condition the impact of economic activity on the environment: the productive structure of an economy, its geographical location, the social consensus on environmental issues in the population, technological adaptation, and the differences in regulations across countries.

Still, voices in favor of degrowth aimed at steering carbon emissions toward a net-zero economy resurface time and again. This paper contributes to the existing literature by examining the welfare implications associated with this strategy in 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). As far as we know, this is the first contribution that uses an eDGE model to evaluate the welfare implications of an additional degrowth strategy amidst the ongoing inertial reduction of carbon emissions. This trend of reduction in emissions is observed in the most advanced economies due to the increasingly widespread adoption of highly efficient green technologies.

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 whether they use green or brown 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 inputs. Furthermore, the model incorporates different types of technological progress aimed at reducing emissions from brown energy sources (both, by decreasing emissions per unit of production and by increasing energy production efficiency) and enhancing total factor productivity.

As a numerical illustration and an application of our model, we calibrate it using data from the Spanish economy, known for having relatively lower carbon emissions per unit of GDP among European economies. Notably, Spain has shown a significant decoupling trend between these variables, a pattern we maintain in our inertial scenario.

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[2] The decoupling between GDP growth and emissions growth since the mid-2000s appears to be the norm in developed countries. However, it is paradoxical that, according to degrowth principles, these countries would be the natural places to implement policies aimed at reducing 'high' consumption.

Our model is set to achieve a carbon emission reduction target aligned with the Paris Agreement. We examine the welfare and macroeconomic impacts of an additional effort to reduce emissions until 2050 using a degrowth strategy, beyond the inertial scenario.

Our findings reveal that, in the absence of policy interventions, technological advancements between 2019 and 2050 is expected to bring about a 32% reduction in emissions compared to 2019 levels. This reduction notably contributes to progress toward achieving the Net Zero Emissions (NZE) target. However, an additional reduction of 38% would be required. This represents the gap in emissions reduction that various degrowth strategies need to bridge.

Among all the considered plans, the degrowth resulting from a decline in TFP causes the most significant reduction in welfare, followed by a strategy based on substituting consumption for leisure. In the latter case, the 24% average decline in GDP from 2019 to 2050 leads to an average 17% decrease in welfare in terms of equivalent consumption. This means that the difference between the welfare under the baseline scenario (where only technological progress occurs) and the average welfare in a scenario in which preferences change in favor of leisure represents 17% of the initial consumption level in the initial steady state. In other words, households should be compensated with 17% of the initial steady-state consumption to be equally well off after the degrowth plan is introduced as they were before. However, this welfare loss escalates to 186% in the long run (2019-2150).

Interestingly, despite its potential unpopularity, a strategy centered on a pronounced increase in the price of fossil fuels demonstrates itself to be the least harmful among all the degrowth strategies.[3]. It incurs a moderate welfare loss of 1.4% between 2019 and 2050 and 8% in the long run, which could transform into a welfare gain of 14% if world economies coordinate their strategies.

This paper is structured as follows. Section 2 offers a comprehensive overview of the model and describes the technology-based scenarios. In Section 3, we delve into the simulation results for the three degrowth strategies, highlighting the significance of distinguishing between the transition period and the long run, as well as the impact of a coordinated descarbonization strategy across economies. Finally, Section 4 presents the main conclusions.

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[3] Although taxing the demand for fossil fuels is not typically favored by advocates of degrowth, who argue that market failures are pervasive, persistent, and linked to the scale of human activity, it is the closest approach within a market economy to emulate the concept of forbidding the use of pollutant inputs in production, a practice more commonly associated with autocratic political regimes.

2. Model description and calibration

In this section, we conduct a brief overview of the most important characteristics of our model along with a description of how it has been calibrated and how we have built a baseline scenario. A detailed description of all model equations and the calibration of all its parameters can be found in Andrés et al. (2024).

2..1 The model

2..1.1 Households

Households provide labor services and utilize their income to purchase consumption goods and invest in various capital goods. The representative household in the model maximizes lifetime utility, determined by its consumption (c_t) and labor hours (h_t), with intertemporal elasticities σ and φ respectively, a preference discount rate (β), and a labor disutility (κ_L).

$$U_t = \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left(\frac{c_t^{1-\sigma}}{1-\sigma} - \kappa_L \frac{h_t^{1+\varphi}}{1+\varphi} \right) \tag{1}$$

Households earn both labor and capital income. The latter is derived from renting out different types of capital (green, brown, and intermediate production capital) to firms at specific rental rates. In addition, households receive returns from holding government bonds. As owners of all firms in the economy, they also earn profits from the production of energy, goods, and services. Households invest their savings in government debt and three types of capital: capital for the production of intermediate goods, capital for generating green energy, and capital for producing brown energy.

2..1.2 Energy producers

The economy produces goods and services using labor, capital, and energy. The production process is structured into different levels. The lowest level represents energy production, resulting in CO2 emissions with different intensities depending on whether they use green or brown technologies.

Green and brown energies are generated by firms in competitive markets utilizing distinct capital through the following technologies:

$$v_t^g = \varsigma_t^g \left(k_{t-1}^g\right)^{\alpha^g} \tag{2}$$

$$v_t^b = \left(k_{t-1}^b\right)^{\alpha^b} \left(m_t^b\right)^{(1-\alpha^b)} \tag{3}$$

where m_t^b is an energy commodity produced abroad (e.g., oil) combined with capital, while ς_t^g denotes the efficiency of green energy production. An exogenous increase in ς_t^g implies a green-biased technological change (i.e., normalizing the efficiency in the production of brown energy to one). We posit that ς_t^g evolves exogenously over time according to the following equation:

$$\varsigma_t^g = \varsigma_0^g \left(1 + g_{\varsigma^g}\right)^t \tag{4}$$

where g_{ς^g} refers to the exogenous annual growth rate of green energy production efficiency.

We posit that carbon emissions over a given period are a function that is increasing in relation to the quantity of brown energy produced [4]:

$$e_t^b = \left(1 - \mu_t^b\right) \gamma_{1t}^b \left(v_t^b\right)^{1-\gamma_2^b} \tag{5}$$

where γ_{1t}^b governs the marginal impact of brown energy production on emissions. A reduced value of γ_{1t}^b can be construed as an enhancement in the emissions efficiency of brown energy producers, contributing to the overall decarbonization of the economy. We introduce an exogenous rate of technological progress, denoted as $g_{\gamma_1^b}$, which shapes the dynamics of emission efficiency:

$$\gamma_{1t}^b = \gamma_{10}^b \left(1 - g_{\gamma_1^b}\right)^t \tag{6}$$

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

If firms pay a tax τ_t^e per unit of emissions, there is an incentive to reduce emissions. The variable μ_t^b represents the proportion of emissions abated by brown energy producers. We assume that the abatement costs of brown energy producers, denoted as z^b, are proportional to energy production:

$$z_t^b = \theta_1^b \left(\mu_t^b\right)^{\theta_2^b} v_t^b \tag{7}$$

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[4] While our emissions are linked to brown energy production rather than aggregate production, they still represent a relatively aggregate measure. For instance, buildings (used for heating and air conditioning) constitute 40% of the energy consumed in the EU, contributing to 36% of energy-related greenhouse gas emissions. To comprehensively assess the distinct impact of emissions from dwellings, a more detailed disaggregation of the final production good into housing and other goods and services would be necessary.

2..1.3 Energy suppliers

The next level involves energy suppliers who bundle a combination of green and brown energy, which they then sell to intermediate goods producers at a price $P_t^{v^y}$. The packaging technology is defined by,

$$v_t^y = \left[\theta^g \left(v_t^g\right)^{\frac{\sigma^x - 1}{\sigma^x}} + (1 - \theta^g)\left(v_t^b\right)^{\frac{\sigma^x - 1}{\sigma^x}}\right]^{\frac{\sigma^x}{\sigma^x - 1}} \tag{8}$$

where v_t^y is the overall supplied energy, and σ^x represents the elasticity of substitution between green and brown energy. The sale price of the energy bundle depends on the composition of the energy types. In a scenario of perfect competition, profits within this sector are nil.

2..1.4 Intermediate and final goods producers

There exists a large number of firms engaged in the production of intermediate goods. These firms operate within a framework of monopolistic competition, creating distinctive goods ($y_t(i)$) through the utilization of capital ($k_t^y(i)$), labor ($h_t(i)$), and energy ($v_t^y(i)$),

$$y_t(i) = A_t^y(i) k_{t-1}^y(i)^{\alpha^y} h_t(i)^{\beta^y} v_t^y(i)^{1-\alpha^y-\beta^y} \tag{9}$$

where $A_t^y(i)$ is total factor productivity at the intermediate goods production level.[5]

Firms in the economy face downward-sloping demand curves and, assuming a symmetric equilibrium, firms choose the same price, inputs, and output so that we can obtain aggregate profits for the intermediate goods producers.

Finally, at the top level, firms package a variety of intermediate goods and sell a homogeneous product for consumption, investment, and public spending. Profits are zero at this level of production.

2..1.5 Environmental and economic damage

Emissions contribute to the atmospheric carbon stock, denoted as x_t,

$$x_t = \eta_t x_{t-1} + e_t + e_t^{row} \tag{10}$$

where e_t corresponds to aggregate domestic emissions (from brown energy production) and e_t^{row} denotes exogenous emissions from the rest of the world. The variable x_t is a

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

measure of kilotonnes (kt) of atmospheric carbon (GtC), and $1 - \eta_t$ is the rate of carbon absorption.

The function describing the influence of the atmospheric carbon stock on total factor productivity is given by:[6]

$$A_t^y = [1 - (d_0 x_t^{d_1})]\widetilde{A}_t^y \tag{11}$$

where the economic damage caused by CO2 accumulation in terms of TFP ($d_0 x_t^{d_1}$) is convex, as in Golosov *et al.* (2014) and Dietz and Stern (2015). Hence, $\widetilde{A}_t^y$ denotes the zero-carbon Total Factor Productivity that evolves exogenously, driven by technological progress represented by $g\widetilde{A}$. The dynamics of $\widetilde{A}_t^y$ are described by the following equation:

$$\widetilde{A}_t^y = \widetilde{A}_0^y \left(1 + g_{\widetilde{A}}\right)^t \tag{12}$$

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

2..1.6 The government

The government finances public spending (g_t) and subsidies for green investments (τ_t^{ig}) through levies such as lump-sum taxes on households (τ_t^h), tariffs on imported energy commodities (τ_t^m), and emission taxes on energy-producing firms (τ_t^e). Therefore, the budget constraint can be expressed as:

$$g_t + \tau_t^{ig} i_t^g = \tau_t^h + \tau_t^m p_t^{*m^b} m_t^b + \tau_t^e e_t \tag{13}$$

2..2 Calibration and baseline scenario

We calibrate the model to mirror specific energy and environmental facts of the Spanish economy in 2010. In alignment with the model's parameters, we define green energy as that which includes all forms of energy free of carbon emissions, encompassing hydraulic, nuclear, and renewable energy. Conversely, coal-fired energy, combined cycle energy, and cogeneration are classified as dirty or brown. Emissions and air pollution metrics are quantified in kilotons of carbon[7], while energy is measured in kilotons of equivalent oil. To facilitate interpretation, we normalize aggregate GDP to 1 million euros, enabling most variables to be expressed in terms of million euros of production. As mentioned earlier, comprehensive details about the calibration can be found in Andrés et al. (2024).

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[6] Although the economy's emissions contribute only to a fraction of global emissions, we include this damage function for comprehensive analysis.

[7] 1 kiloton of carbon is equivalent to 3.67 kilotons of carbon dioxide.

Once we get a numerical solution for the model using the calibrated parameters, 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 Spanish observed changes in GDP, in carbon emissions, and in the ratio of green to brown energy production from 2010 to 2019.

Between 2010 and 2019, Spain's real GDP grew annually at a rate of 1.14%, while carbon emissions decreased yearly by 1.39%, and the ratio of green energy production to brown energy increased by 1.51 percentage points per year. We attribute these changes to the three types of technological progress present in our model, specifically, technological progress that increases total factor productivity ($g_{\widetilde{A}}$), technological progress biased toward green energy production (g_{ς^g}), and technological progress that reduces emissions per unit of energy production ($g_{\gamma_1^b}$).

Under the assumption that technological progress is unknown by economic agents, we introduce unanticipated series for $\widetilde{A}_t^y$, ς_t^g, and γ_{1t}^b over a 10-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 $\widetilde{A}_0^y$, ς_0^g, and γ_{10}^b 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 observed increase in GDP, the decrease in 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.

Figure A.1 in Appendix A provides an overview of how the model captures the decline in emissions when considering all three types of technological progress. Interestingly, 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.

Next, we use the previously calibrated growth rates of technological progress to input into the model year by year, enabling us to project emissions from 2019 to 2150. Figure A.2a visually represents the *baseline* scenario until 2050, alongside two alternative scenarios that consider different paths for technological progress. In the optimistic scenario, we increase the growth rates of exogenous green bias technology progress and emissions efficiency by one-third, while keeping the growth rate of total factor productivity (TFP) unchanged. Conversely, in the pessimistic scenario, we reduce these growth rates by one-third. This definition of the optimistic and pessimistic scenarios yields a notable impact on the evolution of emissions.

This projection of emissions goes hand in hand with the corresponding projections of macroeconomic, energy, and environmental variables in the model. Figure A.2b in Appendix A presents the evolution of GDP across the three scenarios considered. As can be seen, the different technological scenarios have a relatively minor effect on the evolution of output. Figure A.2c highlights the progressive increase in the ratio of green to brown energy production driven by technological advancements.

According to Brienen *et al.* (2020) over the past 50 years, terrestrial ecosystems have been responsible for the removal of about one third of anthropogenic carbon emission. Hence, to set the emissions target, 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.[8] 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 1 outlines the percentage decline in emissions anticipated from 2019 to 2050 due solely to expected technological advancements across the three scenarios. Furthermore, it incorporates the supplementary efforts required beyond the envisioned 2050 benchmarks to fulfill the emission reduction objective. In the baseline scenario, absent policy interventions, the envisaged technological progressions between 2019 and 2050 are poised to deliver a 32.1% reduction in emissions compared to the levels of 2019. This contribution is notably substantial in advancing towards the overarching 70% reduction target. However, an additional reduction of 37.9% must be sought through the implementation of different emissions mitigation strategies. This necessity arises as the impact of technological progress in decarbonization seems insufficient to offset with the necessary speed the emissions resulting from economic growth.[9] In this regard, a possibility considered by various studies would be to use strategies based on degrowth. Three of these strategies are evaluated in the following section.

2..3 Welfare variation

Welfare changes play a pivotal role in our results. Here, we elaborate on the metric used to express these changes in welfare.

Let U^{ss} denote the expected discounted lifetime utility corresponding to a steady-state solution with "no technological change and no policy", where the initial level of consumption and working hours remains constant over time:

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[8] This target is less strict than the one set by NPEC (European Commission, 2023)

[9] Notably, accounting for policy implementation may modify the relative contributions of technology and policy toward emissions reduction

$$U^{ss} = \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left(\frac{[c^{ss}]^{1-\sigma}}{1-\sigma} - \kappa_L \frac{[h^{ss}]^{1+\varphi}}{1+\varphi} \right) \tag{14}$$

where c^{ss} and h^{ss} represent the consumption and hours in the constant steady-state solution. We then calculate Λ_t^b to equalize the welfare between the constant steady-state solution and the baseline scenario corresponding to technological change:

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left(\frac{[(1-\Lambda_t^b)c^{ss}]^{1-\sigma}}{1-\sigma} - \kappa_L \frac{[h^{ss}]^{1+\varphi}}{1+\varphi} \right) = \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left(\frac{[c_t^b]^{1-\sigma}}{1-\sigma} - \kappa_L \frac{[h_t^b]^{1+\varphi}}{1+\varphi} \right) \tag{15}$$

here, c_t^b and h_t^b represent consumption and hours in the technological change baseline scenario.

It is important to note that a negative Λ_t^b signifies an increase in welfare in the baseline scenario compared to the constant steady-state solution. It can be interpreted as the proportion of initial consumption that a household should receive if, in the absence of technological change, they wish to reach the same level of well-being as under a scenario with technological change. Therefore, a negative Λ^b is associated with an increase in welfare in terms of equivalent consumption due to technological change.

In a parallel vein, we can derive Λ_t^p to homogenize welfare between the "no technological change and no policy" solution and the "technological change plus policy" scenario:

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left(\frac{[(1-\Lambda_t^p)c^{ss}]^{1-\sigma}}{1-\sigma} - \kappa_L \frac{[h^{ss}]^{1+\varphi}}{1+\varphi} \right) = \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left(\frac{[c_t^p]^{1-\sigma}}{1-\sigma} - \kappa_L \frac{[h_t^p]^{1+\varphi}}{1+\varphi} \right) \tag{16}$$

where c_t^p and h_t^p denote consumption and hours in the 'technological change plus policy' scenario. The value of Λ_t^p can be negative, indicating that the policy, when combined with technological developments, increases welfare compared to an environment with no policy and no technological progress. Alternatively, it can be positive, signifying that the cost of the policy outweighs the benefits of technological progress, resulting in decreased welfare compared to the constant steady-state solution. However, it is noteworthy that Λ^p is often greater than Λ^b since the policy typically entails some welfare cost.

Finally, we can define our measure of welfare loss as

$$\Lambda_t^{p-b} = \Lambda_t^p - \Lambda_t^b \tag{17}$$

Typically, $100\Lambda_t^{p-b}$ is positive and can be interpreted as the percentage of initial consumption needed to compensate for the loss in welfare due to the introduction of the policy compared to the baseline technological change scenario. Conversely, a negative Λ^{p-b} represents a gain in utility compared to the baseline and can be interpreted as the percentage of initial consumption that should be subtracted from the policy scenario consumption to achieve parity after and before the policy's introduction.[10]

3. Degrowth plans

Degrowth theory does not present a uniform set of proposals. Furthermore, its predominantly narrative approach complicates the task of translating these proposals into a model-based framework. Therefore, we approximate here three distinct degrowth strategies aimed at achieving net-zero emissions: penalizing fossil fuel demand, substituting aggregate consumption with leisure, and reducing GDP through a sequence of negative shocks to total factor productivity.[11] We explore the economic and welfare implications of these strategies.[12] To ensure fairness in comparing the economic impacts of these plans, we maintain consistency in our simulation strategy across all three.

We assume that all the degrowth plans start suddenly but, since then, they are fully anticipated by the agents. Additionally, the plans are progressively implemented with a linear increase in intensity until 2050, remaining constant thereafter.

By comparing the expected evolution of relevant variables with and without the implementation of the degrowth plans (referred to as the baseline scenario), we evaluate both the transitional effects of the plan from 2019 to 2050 and its long-run effects between 2019 and 2150.[13] With this analysis, we aim to shed light on the potential economic implications of degrowth strategies in bridging the emissions gap and achieving the objectives set forth in the Paris Agreement.

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[10] Note that, although a positive Λ_t^{p-b} represents a welfare loss, as is the case for Λ_t^b and Λ_t^p, unlike these, it is not bounded to be lower than 1.

[11] Other, less extreme perspectives associated with degrowth, such as the focus on material reuse to mitigate environmental impacts (e.g., plastics, cardboard) or the awareness of individual or group behaviors (e.g., substituting business trips), likely contribute to reducing atmospheric carbon. While these aspects are not explicitly discussed in the paper, their effects are partially captured in our calibration strategy for the benchmark scenario.

[12] We focus on the baseline scenario. However, in the pessimistic (optimistic) scenario, economic harm would increase (decrease) non-linearly.

[13] For the simulations, we use Dynare 6.0 running in Matlab R2019a.

3..1 Reducing emissions by penalizing fossil fuels demand

Brown energy production in our model relies on an imported commodity, represented by m_t^b (such as oil or gas). The price of this commodity (relative to CPI) is determined in international markets and is considered exogenous in our model. Thus, the government has the option to apply a tariff on imports of this commodity or impose a tax/subsidy on its use, as a means to reduce the consumption of brown energy and, consequently the level of carbon emissions to the desired target. Among the various interpretations of degrowth presented in van den Bergh (2011), penalizing fossil fuel demand can be classified under the category of physical degrowth, albeit indirectly since besides reducing polluting emissions it incentivizes the use of alternative sources of (clean) energy.

In particular, we assume that the fiscal authority announces a strategy of progressively increasing the relative price of the commodity linearly until the objective of carbon emission is reached in 2050, at which point the relative price will stabilize. Depending on the international evolution of this price, the government may need to impose taxes on the imports/use of the commodity in some years and provide subsidies in others. These taxes are reimbursed to households, while subsidies are charged to them. While implementing this plan, the government does not care about the effects on consumption, GDP, or other macroeconomic aggregates. The government's sole concern is to achieve a continuous reduction of emissions until reaching net zero.

Based on our findings, the price of the commodity (relative to the CPI) required to meet the emission target would need to increase by 133%. Figure A.3 in Appendix A illustrates the reduction in emissions resulting from the consistent maintenance of a high relative price for imported commodities. The Net Zero Emissions (NZE) target is achieved by 2050. The graph further demonstrates that emissions continue to decline after 2050, due to the ongoing influence of emissions-reducing technological progress.

Table 2 presents the average macroeconomic effects during the period 2019-2050. This strategy reduces brown energy production during the 2019-2050 period by approximately 31% compared to the baseline on average, increases green energy production by 6.4%, and increases the cost of the energy mix by around 12%. The total reduction in emissions during the period is 29%, while the cumulative loss of GDP is calculated to be only -0.8 percentage points. In addition to the NZE target, this plan also successfully reaches the intermediate Green Deal target by 2030.[14]

Figure 3 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.

every year from 2019 to 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 and consumption will be 1.5% lower compared to the baseline scenario. The last subplot in the figure displays the welfare dynamics in terms of the percentage of initial consumption required to compensate for the loss in utility with respect to the baseline scenario (see expression 17). The welfare cost increases over time and would be around 3% in 2050 in terms of equivalent consumption.

Table 3 compares the welfare impact of various degrowth plans in terms of equivalent consumption. The initial section details the average percentage change in equivalent consumption between 2019 and 2050, while the subsequent part examines the long-term welfare outcomes for the period 2019-2150. In addition, it shows the magnitude of policy instrument adjustments required to achieve the emission target. We distinguish between a *non-coordination* and a *coordination* scenario. In a scenario involving coordination, we operate under the assumption that the rest of the world adopts an identical emissions reduction trajectory as Spain for each of the proposed plans. We modelize this by doing the rest of the word emissions endogenous and proportional to the Spanish ones, such that the benchmark proportion between emissions in Spain and in the rest of the world remains constant.[15]

Between 2019 and 2050, the average reduction in welfare amounts to 1.4% in terms of equivalent consumption. This reduction intensifies in the long run, surpassing 8% of consumption. However, in a coordinated scenario where global emissions decrease gradually, the carbon stock in the atmosphere follows suit, alleviating the negative impacts of global warming on the economy. Although this is not sufficient to reverse the decline in welfare caused by the increased fossil fuel prices during the 2019-2050 period (welfare still decreases by 1.15% in terms of equivalent consumption), the long-term effects result in an average welfare increase equivalent to 14.10% of consumption. Figure 4 displays the evolution of welfare over time, in terms of consumption equivalence, under coordination and non-coordination, with a negative sign indicating a welfare gain.

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[15] We should note that our analysis does not consider the second round of a comprehensive general equilibrium approach on economic activity and emissions. Therefore, this exercise should be regarded as a simplified approach, which could underestimate the broader macroeconomic effects and the influence on emissions that could arise from coordination.

3..2 Reducing emissions by substituting aggregate consumption for leisure

The second degrowth strategy we examine involves a departure from traditional economic growth by reducing aggregate consumption. This strategy is implemented by introducing a wedge in the utility function that affects the marginal utility of hours and consumption. This wedge represents a progressive shift in household preferences, emphasizing leisure over consumption, with the ultimate goal of achieving the long-term emissions target. Specifically, we introduce an exogenous variable ς_t^h as a shifter in the utility function. A higher value of ς_t^h signifies a reduced emphasis on consumption relative to leisure time within household preferences. This adjustment in the utility function encapsulates the essence of degrowth, fostering a reduction in global consumption and production. The following expression presents the instantaneous utility function, wherein the wedge $(1-\varsigma_t^c)$ influences the consumption term.[16]

$$U_t = \left(\frac{(1-\varsigma_t^c) c_t^{1-\sigma}}{1-\sigma} - \kappa_L \frac{h_t^{1+\varphi}}{1+\varphi} \right) \tag{18}$$

Figure A.4 in Appendix A illustrates the trajectory of ς_t^c along the emission path. The achievement of the Net Zero Emissions (NZE) target of 2050 requires a linear reduction of nearly 89% in the relative preferences for consumption by 2050. Figure 5 displays the full dynamics of GDP compared to the baseline.[17]

This strategy incurs substantial costs in terms of consumption and GDP, resulting in average reductions of 17% and 24% between 2019 and 2050, respectively (see Table 2). However, there are some positive outcomes. Dirty energy production decreases by 29% owing to an overall reduction in total energy demand by 21%. Furthermore, the cumulative reduction in emissions during this period is slightly less than that achieved through the increase in the price of fossil fuels, just under 26%. Notably, in contrast to the previous strategy, there is a reduction in the price of energy.

Figure 6 illustrates the percentage deviations of selected variables from the baseline over the transition period. By 2050 GDP is almost 50% lower than in the baseline. Hours also experience a sharp reduction, as households substitute consumption for leisure. The last subplot in the figure depicts the welfare dynamics in terms of the percentage of consumption required to compensate for the loss in utility if preferences remained the same

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[16] There are alternative methods of introducing this wedge in the utility function, which do not substantially alter the overall findings. Furthermore, when assessing the change in welfare resulting from the policy based on initial preferences, as we have done, the strategy can also be construed as a government-initiated reduction in maximum working hours.

[17] GDP is normalized to 1 in 2019. The results in terms of GDP are similar to those obtained by Warlenius (2023) with a different methodology

as in 2019. This can be interpreted as if the projected reduction in consumption and working hours were not the result of optimal household decisions but rather an imposition by authorities. Despite the increase in leisure, welfare virtually halves by the year 2050.

According to Table 3, the average welfare experiences a decline of 17% (in equivalent consumption terms) during the period 2019-2050 in the baseline scenario. However, in the long run, between 2019 and 2150, the reduction in welfare becomes significantly more pronounced, reaching an average of 200% (in terms of equivalent consumption) in the baseline scenario. Although a coordination strategy alleviates part of the cost, the gain from reduced global emissions does not compensate for the substantial welfare cost caused by degrowth (we will revisit this issue later).[18]

3..3 Reducing emissions by reducing total factor productivity

The third strategy involves an endogenous fall of GDP to ensure NZE in 2050. In a general equilibrium framework, as in our case, this should be modeled by a decrease in the total factor productivity of the economy. Specifically, over the baseline technological progress, as captured by the expression (12), we implement a linear reduction in total factor productivity ($\widetilde{A}_t^y$). This alteration forces the economy to follow a downward trajectory in production and consumption, ensuring a decline in output and energy emissions until it reaches the net-zero target. Unfortunately, the model struggles to achieve the NZE by 2050, as the required shock on ($\widetilde{A}_t^y$) drives some variables close to the zero bound throughout the dynamic path. Thus, we have applied the most significant shock to total factor productivity that the model allows. Figure A.5 in Appendix A depicts the consequences of a 60% linear reduction applied over $\widetilde{A}_t^y$,[19], where only 81% of the NZE target is accomplished by 2050. Moreover, this target is delayed by a decade, extending it to 2060. Consequently, this simulated plan is the least ambitious of the three considered in the study in terms of satisfying the 2050 objective.

Figure 7 shows that although this strategy fails to achieve NZE by 2050, it incurs the most significant negative impact on GDP over the long run with respect the baseline. In fact, GDP declines from its initial value and does not recover afterwards, provoking a huge loss in GDP with respect to the baseline.

The final column in Table 2 demonstrates the relatively modest impact of this plan

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[18] To facilitate comparisons across different plans, we have excluded tipping points. Depending on the intensity of the discontinuities caused by increasing temperature on economic activity, even a significant welfare cost might be justified to avoid tipping points. Thus, Table 3 provides metrics for comparing the likely welfare cost of tipping points.

[19] The actual fall in A_t^y is lower than 60% as we do not entirely eliminate the influence of $g_{\widetilde{A}}$

on emissions during the period 2019-2050, despite a substantial average decline of 42% in consumption compared to the baseline. Interestingly, during the transition period, similar to the effect observed with an increase in the price of fossil fuels, this strategy prompts a significant shift from dirty to clean energy production. However, in this case, it accompanies a notable reduction in the price of energy compared to the baseline. Figure 8 illustrates the complete trajectory of relative changes in key variables compared to baseline.

Among all the plans considered, the degrowth induced by a decline in TFP leads to the most severe reduction in welfare. As Table 3 shows, the loss of welfare represents 67% in terms of equivalent consumption, under a non-coordinated strategy, and plummets by 419% in the long run. Even a globally coordinated strategy would only slightly mitigate a tiny fraction of this substantial welfare decline. [20]

3..4 Global coordination: effects on welfare and temperature

Coordination serves different roles in welfare and economic activity depending on the degrowth plan, despite alleviating the costs linked with emissions reduction. In Figure 9, we present evidence of the welfare benefits derived from coordination. The columns represent the three plans, while the rows illustrate different aspects of the welfare gains of coordination from 2019 to 2150. Notably, the welfare gains from coordination are most significant for the strategy that focuses on increasing the price of fossil fuels. For the degrowth strategy involving substituting consumption for leisure, the coordination's welfare gains by 2150 are approximately 8 times higher than those for the plan reducing the economy through lower TFP.

The second and third rows of subplots in the figure depict the dynamic paths of consumption and working hours, which ultimately determine welfare. Coordination is only effective in reversing the negative impact of the plan when prices in fossil fuels are increased to achieve NZE. For the other two plans, the welfare correction falls significantly short of fully compensating for the loss, especially concerning the decline in consumption.

Figure 10 illustrates the modeled evolution of temperature across four scenarios: the baseline scenario with no policy intervention and three degrowth plans under the assumption of full coordination.

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[20] The zero growth target is a variation of degrowth based on limiting TFP evolution. We attempted to eliminate $g_{\widetilde{A}}$ from Equation (12) and compared it with the baseline scenario in which the technological progress rate affecting TFP is fully operational. The results indicate that halting TFP and GDP growth implies a cost, in terms of consumption needed to compensate for the welfare loss compared to the baseline scenario, of about 39% until 2050 and 395% in the long run.

Utilizing a conventional assumption in the literature[21], we establish a relationship between the atmospheric carbon stock and temperature evolution through the following expression:

$$T_t = \lambda \frac{\log(\frac{x_t}{\bar{x}})}{\log(2)} \tag{19}$$

where $\bar{x}$ represents the pre-industrial atmospheric carbon concentration, and λ denotes the sensitivity parameter reflecting the temperature's response to changes in carbon stock. Although the literature commonly assumes $\lambda = 3$, our analysis indicates that a value of $\lambda = 2.3$ better aligns with the historical relationship between carbon concentration and temperature since 1850 (see Andrés *et al.*, 2024).

In the absence of intervention, the baseline scenario predicts a progressive temperature increase, reaching 3.2 degrees Celsius above pre-industrial levels by 2150. However, the three degrowth plans demonstrate a mitigating effect on this trend. By 2050, the temperature rise is curtailed to 1.4 degrees Celsius (1.6 degrees for the TFP-based plan), a contrast to the 1.8-degree Celsius increase in the baseline scenario. Over time, these figures gradually diminish, reaching 0.9 degrees Celsius (0.7 degrees for the TFP-based plan) by 2150.[22]

4. Conclusions

Our study delves into the macroeconomic and welfare ramifications of various degrowth strategies to achieve the goal of net zero emissions (NZE) by 2050. Strict degrowth strategies aimed at compensating for a reduction in the consumption of goods and services through a reduction in the consumption of goods and services compensated by an increase in leisure, or by strong impediments against conventional economic growth, lead to a notable decline in welfare. Specifically, in our simulations, this strategy would result in an average 24% decrease in GDP and a 17% reduction in consumption from 2019 to 2050. This causes an average 17% decrease in welfare (in terms of the amount of consumption necessary to compensate for the loss in utility), which, under moderately favorable assumptions, would escalate to 186% over the long term (2019-2150).

Reducing the size of the economy by penalizing the drivers of Total Factor Produc-

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[21] See Golosov *et al.* (2014).

[22] In the case of a zero growth strategy, we find that while this proposal is capable of curbing the ever-growing path of the baseline atmospheric temperature under a coordinated strategy, it does not act swiftly enough to reverse before 2150 the observed increase over pre-industrial levels in the temperature observed by the beginning of the period.

tivity (TFP) growth exacerbates the adverse effects of degrowth. Our findings highlight an average reduction of over 40% in consumption during the transition phase. Coupled with a significant decrease in leisure time, this situation leads to an average welfare decline of 67% in terms of equivalent consumption between 2019 and 2050. Over the extended period from 2019 to 2150, the impact is more pronounced, surpassing 400% in terms of equivalent consumption. Interestingly under this strategy, as well as in the degrowth-by-increasing-leisure strategy above, international coordination does very little to alleviate this substantial welfare cost.

Strategically reducing the demand for polluting fossil fuels without sacrificing consumption or technological advancement appears to align with more nuanced interpretations of degrowth. In our model, we achieved a reduction in fossil fuel demand by imposing taxes on the price of the imported commodity. As the fossil price (relative to CPI) rapidly and intensively increases, the demand for pollutant income falls, which is the standard way the policy in a market economy has to simulate a ban on the use of pollutants. While similar policies have been attempted previously, they often sparked significant social backlash (e.g., the *gilets jaunes* movement in France), leading to the revocation of such measures shortly after implementation. However, our findings suggest that this particular strategy exhibits notably less detrimental welfare effects compared to other degrowth policies. During the transition period, the welfare cost, measured in terms of equivalent consumption, remains at a very manageable 1.4%. Although over the longer period from 2019 to 2150, this welfare cost increases to 8% in equivalent consumption, a globally coordinated strategy could transform this welfare cost into a gain of 14% in the long run. It is useful to keep in mind that we only have real experience with this type of strategy, as the other two strategies studied have not intentionally been carried out in reality. Although they would imply navigating uncharted waters, the huge welfare cost we obtain warns us about the advisability of embarking on such a voyage. Given these welfare costs, it is more appropriate to pursue sustainable growth by replacing fossil fuels with renewable energies and by recycling, as advocated by proponents of the circular economy.

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Figures

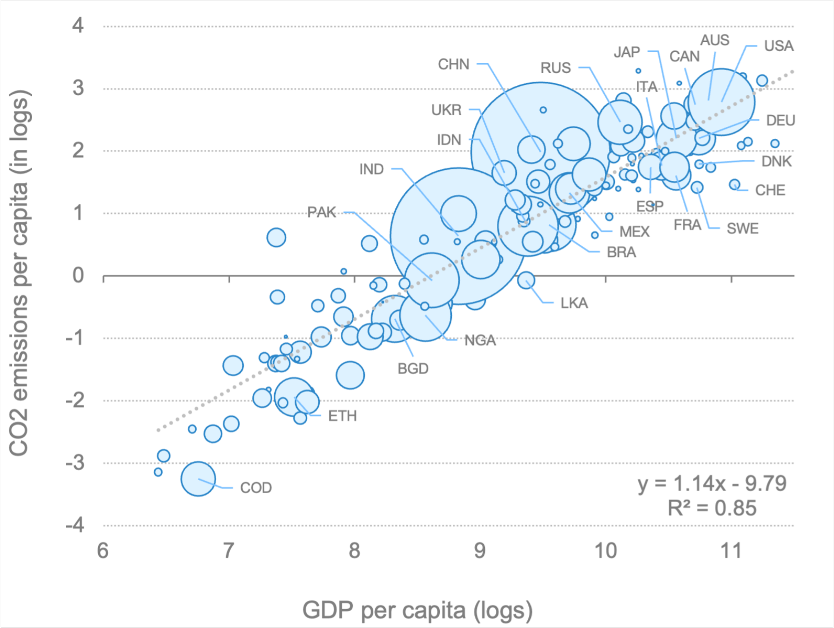


Figure 1: *GDP per capita, in PPP, and CO2 emissions per capita, 2018. Land-use change is not included. Circles sized by population. Source: own elaboration based on Our World in Data (2024), Global Carbon Budget (2023) and Bolt and van Zanden (2020).*

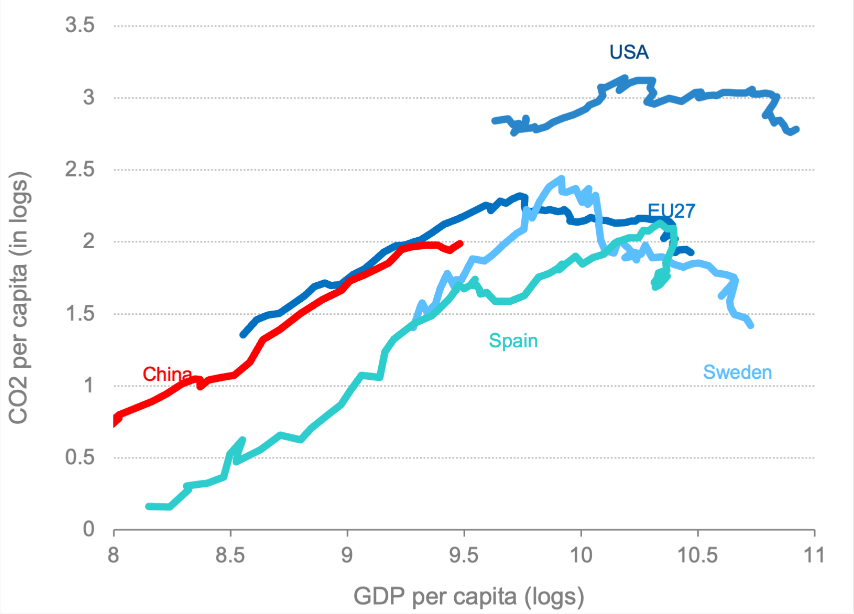


Figure 2: *GDP per capita, in PPP, and CO2 emissions per capita in selected countries, 1950-2018 (except China from 1983). Source: own elaboration based on Our World in Data (2024), Global Carbon Budget (2023) and Bolt and van Zanden (2020).*

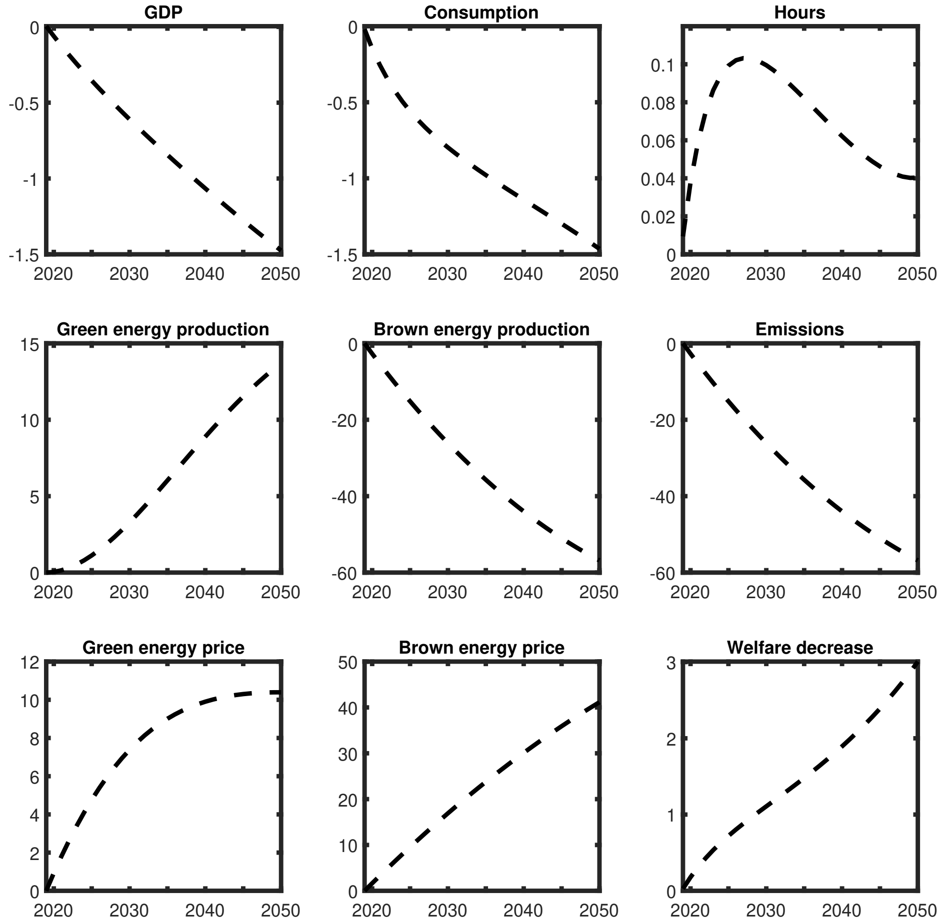


Figure 3: *Dynamic macroeconomic effects resulting from a linear increase in fuel price (percentage deviations with respect to the baseline period)*

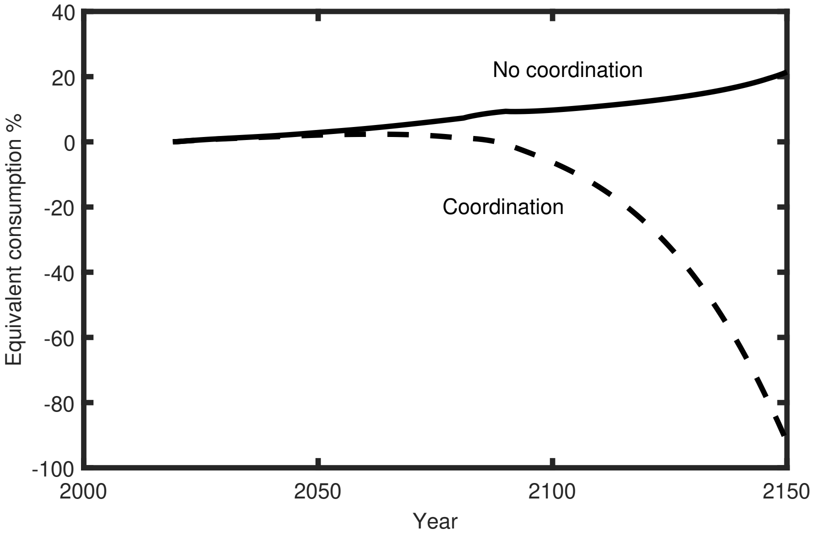


Figure 4: *Dynamic welfare effects of a linear increase in the fuel price (percentage variations in equivalent consumption)*

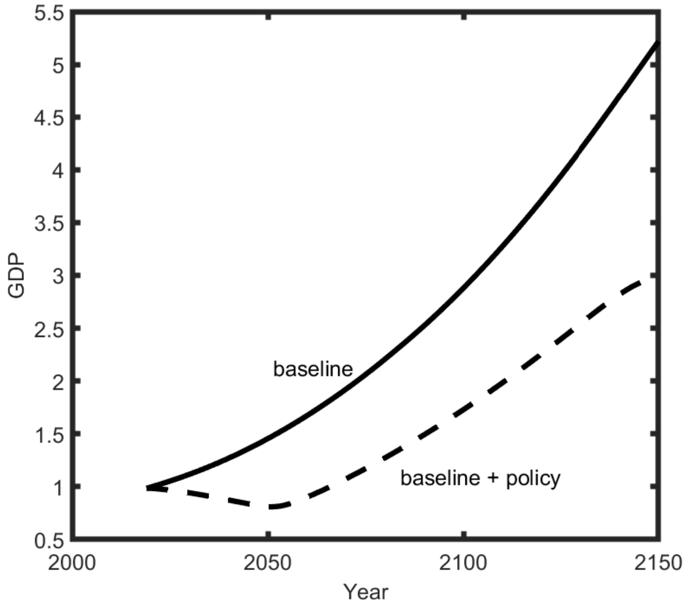


Figure 5: *Decrease in relative preferences for consumption: GDP*

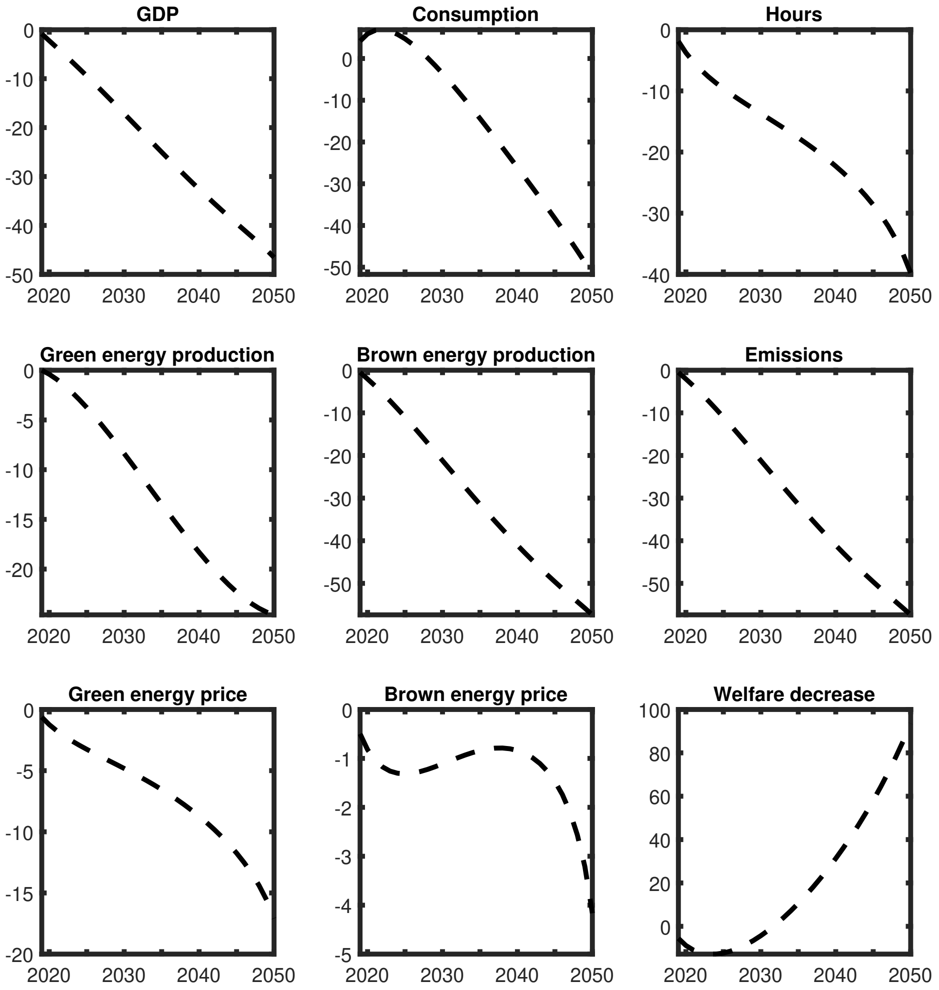


Figure 6: *Dynamic macroeconomic effects resulting from a linear decrease in the relative preferences for consumption (percentage deviations with respect to the baseline period)*

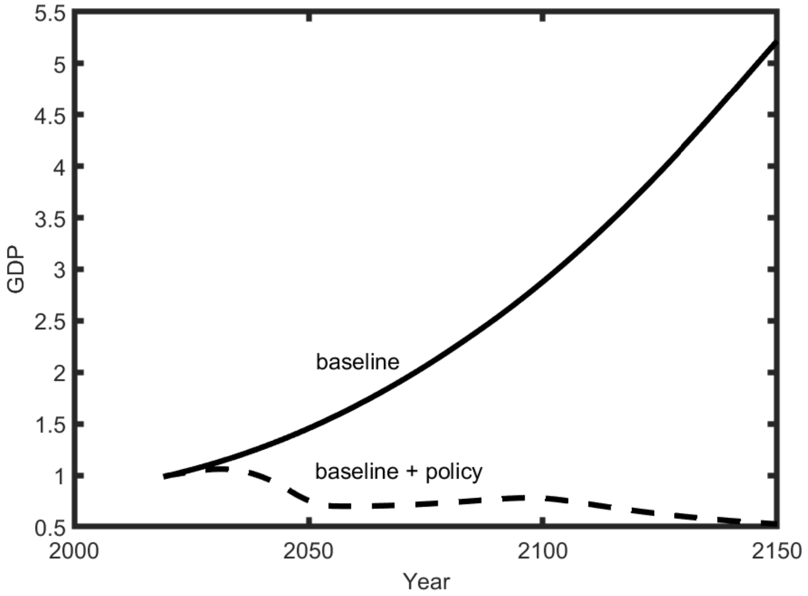


Figure 7: *Decrease in TFP: GDP*

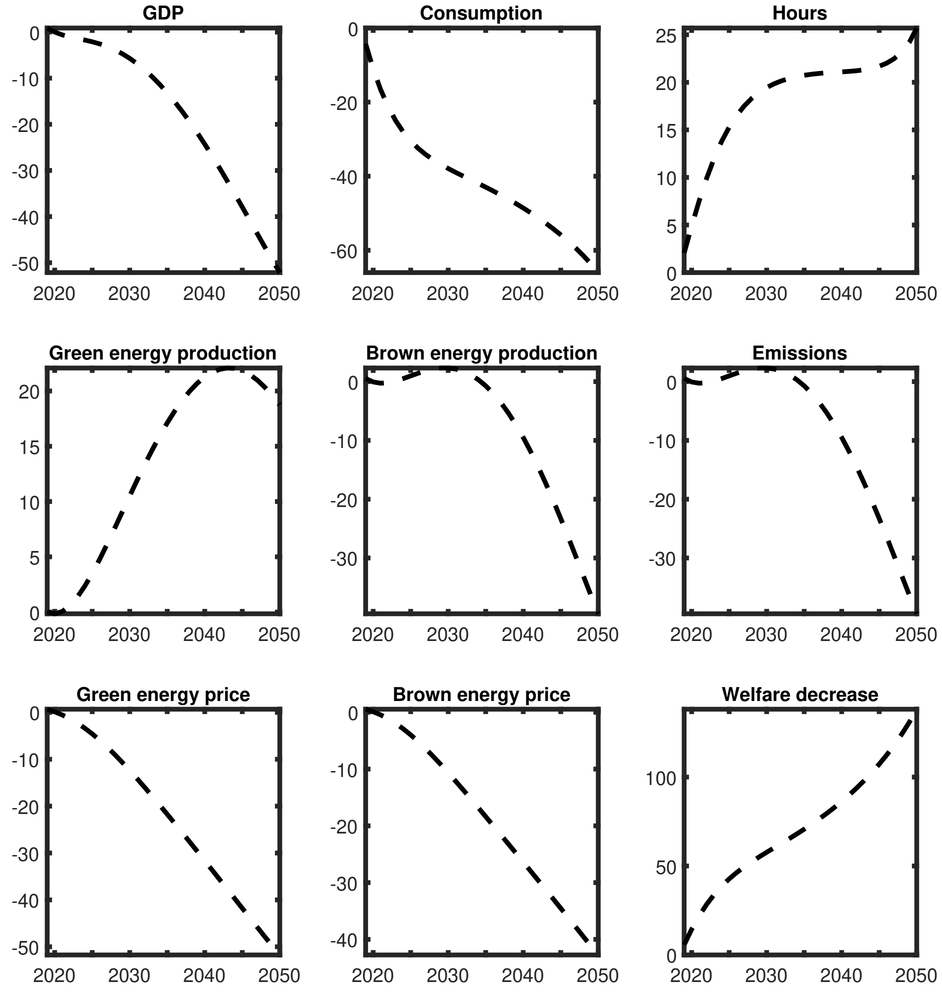


Figure 8: *Dynamic macroeconomic effects resulting from a linear increase in TFP (percentage deviations with respect to the baseline period)*

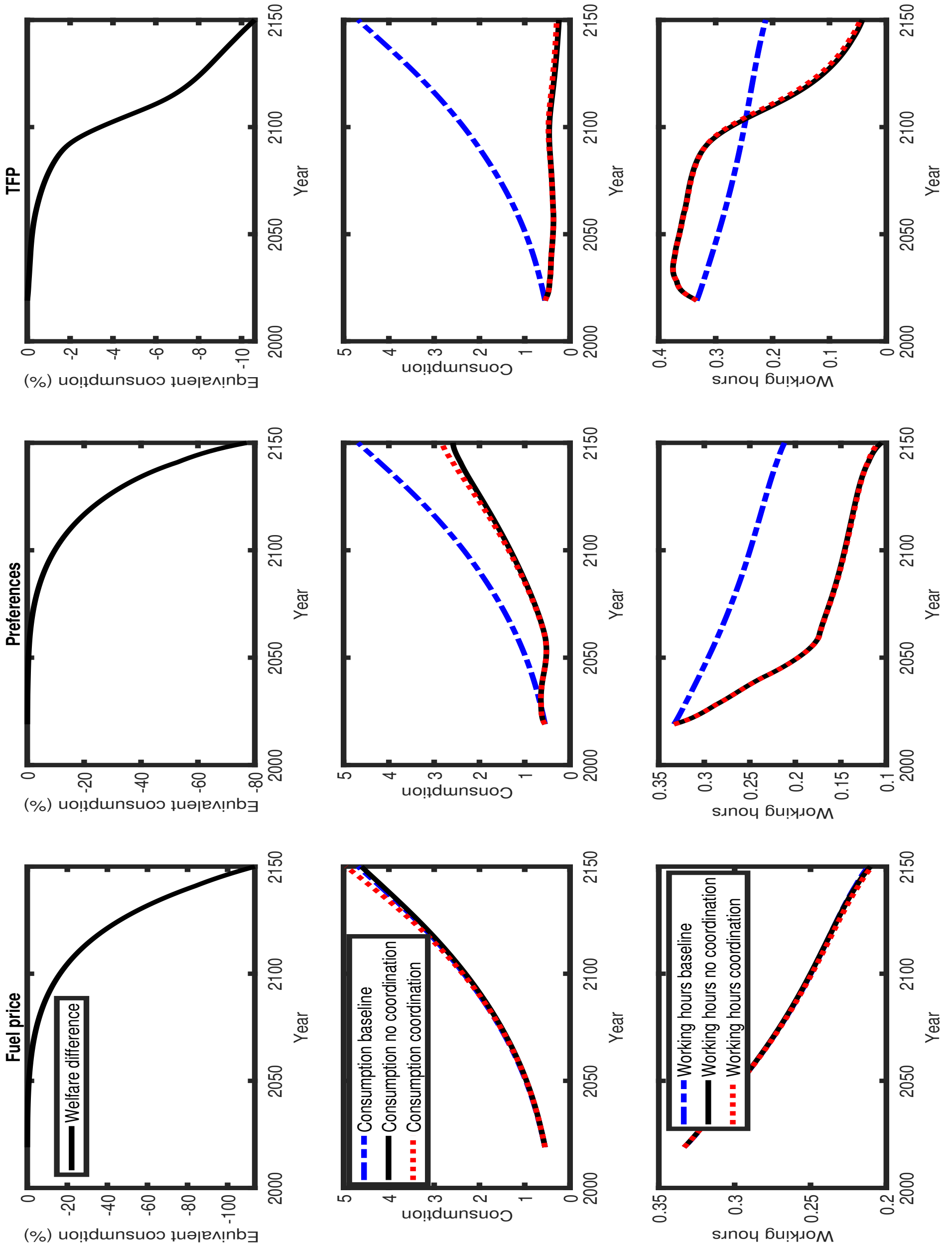


Figure 9: *Coordination vs non-coordination: Welfare, consumption and leisure*

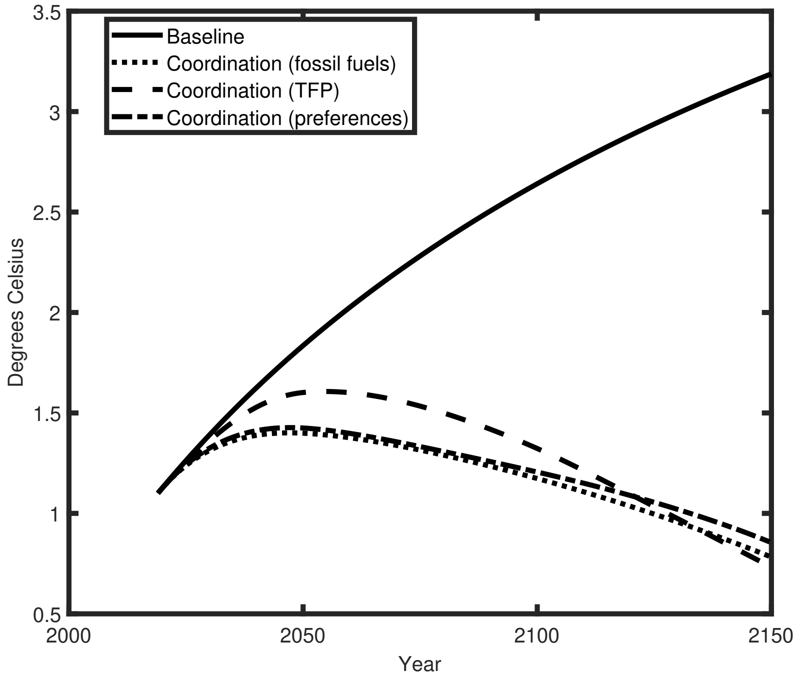


Figure 10: *Temperature above pre-industrial levels: baseline and degrowth plans under coordination*

Tables

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

Table 1: *Required emissions reduction in 2050 to achieve the emissions target (percentage decrease with respect to 2019)*

	Degrowth: Fuel Price	Degrowth: Leisure	Degrowth: TFP
Emissions	-28.77	-25.89	-5.95
GDP	-0.80	-24.08	-17.89
Consumption	-0.92	-17.37	-41.71
Green energy production	6.43	-13.34	14.17
Brown energy production	-31.48	-28.64	-7.44
Energy mix distribution	-12.16	-20.72	3.70
Green energy price	7.21	-6.57	-20.44
Brown energy price	21.19	-1.18	-17.53
Energy mix price	12.39	-4.39	-19.32
% of target by 2050	100	100	81
Year to reach the 2050 target	2050	2050	2060
% of Green Deal target by 2030	121	121	95

Table 2: *Macroeconomic effects during the period 2019-2050 resulting from different degrowth plans (percentage deviations from accumulated baseline paths)*

	Fuel price		Leisure		TFP	
	Price increase	Welfare	Consumption preference	Welfare	TFP decrease (over baseline)	Welfare
2019-2050	(%)	(%)	(%)	(%)	(%)	(%)
No coordination	133	1.39	-89	17.19	-60	67.17
Coordination	133	1.15	-89	17.03	-60	67.06
2019-2150						
No coordination	133	8.15	-89	199.70	-60	419.36
Coordination	133	-14.10	-89	186.05	-60	415.96

Table 3: *Average welfare effects of different degrowth plans from 2019-2050 and from 2019-2150. Welfare expressed as percentage changes in equivalent consumption (negative values = gain, positive values = loss)*

Appendix A Other Figures

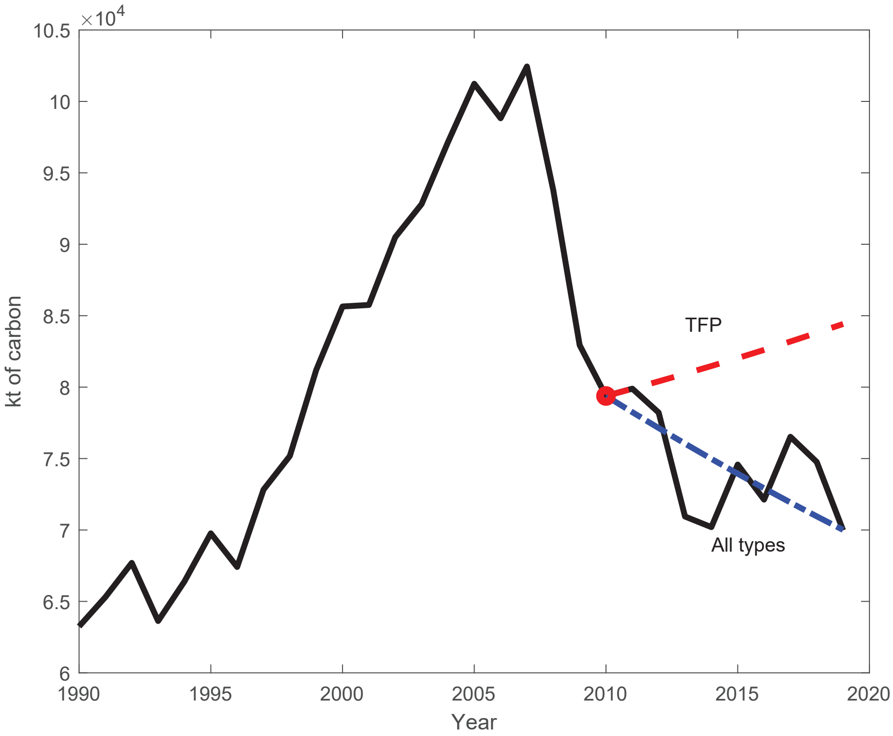
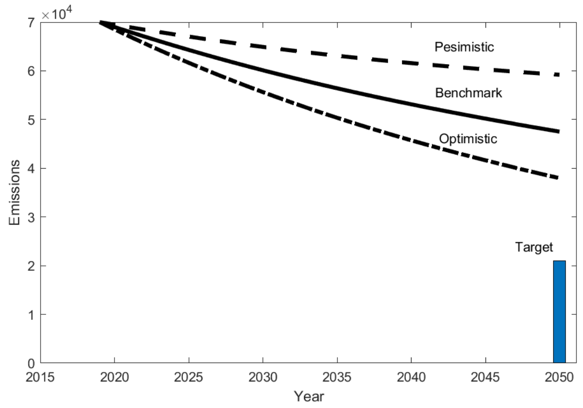
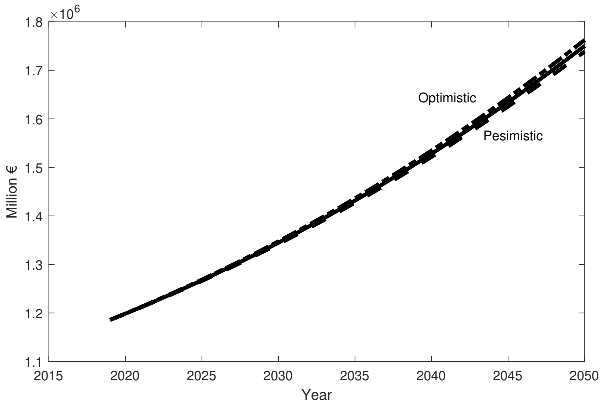


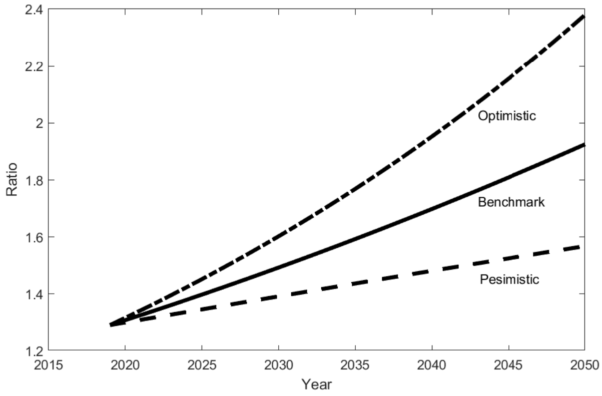
Figure A.1: *Observed and projected evolution of emissions, comparing the actual trend since 2010 to a model scenario with TFP growth and decarbonization. Source: IEA-EDGAR (2022) and own analysis*



(a) *Projected carbon emissions (kt)*



(b) *Projected GDP*



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

Figure A.2: *Baseline, optimistic and pessimistic scenarios 2019-2050*

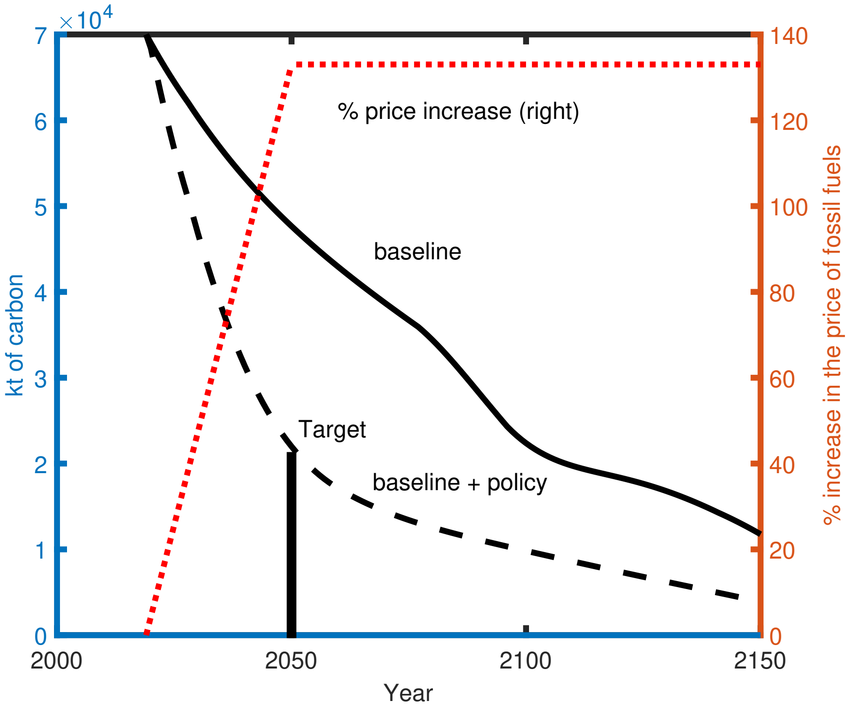


Figure A.3: *Increase in the price of fossil fuels: Emissions*

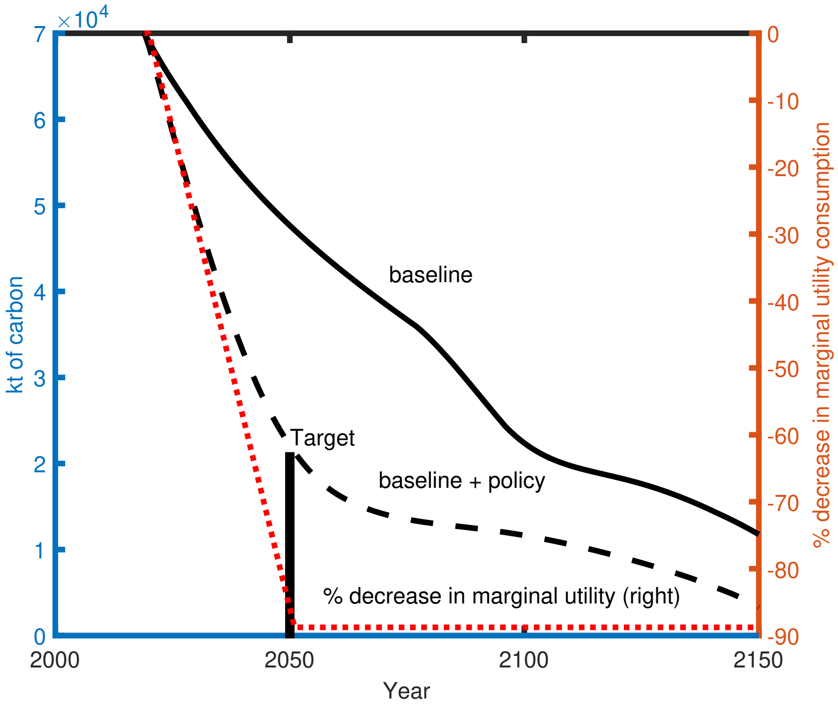


Figure A.4: *Decrease in relative preferences for consumption: Emissions*

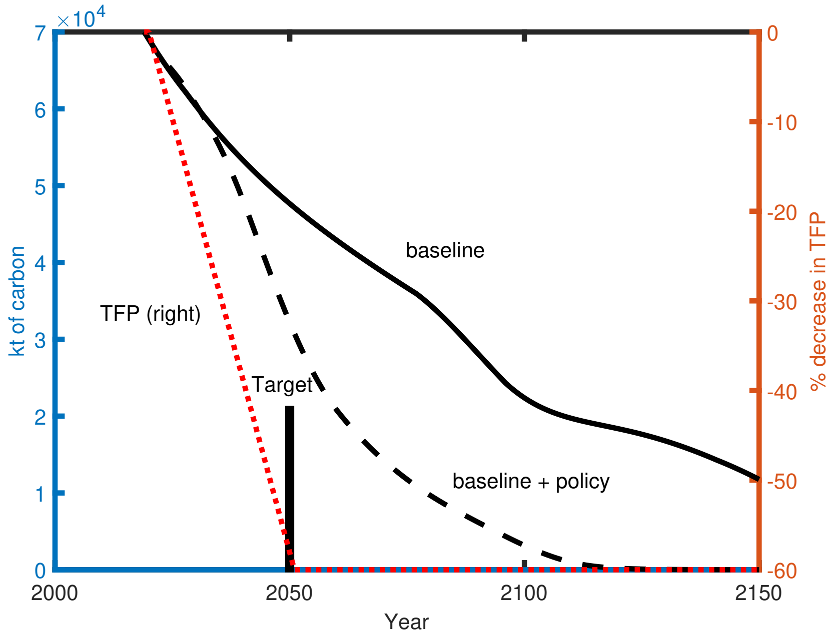


Figure A.5: *Decrease in TFP: Emissions*