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Economic Growth and Equity in Anticipation of Climate Policy*

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Abstract

We study the role of the anticipation of climate policies on equity and economic growth in a numerical model of general equilibrium. The presence of the anticipation period allows the agents to adjust their choices before policy implementation. This period might change the equilibrium dynamics. It might also impact the redistribution of wealth in the economy. We choose the Swiss economy to exemplify and analyze these effects. The supply-side of the economy adjusts by redirecting the investments to "cleaner" sectors with a lower tax burden and higher profitability. On the demand side, welfare impacts by households vary according to their principal source of income. Households that have a high share of their income from capital rents benefit more from the policy's announcement than others do. We find that, for the most stringent climate policies, the effect of anticipation is strongly positive but also regressive.

Keywords: Climate policy, Environmental tax, Economic inequality, Endogenous growth, CGE Modelling

JEL Codes: C63, E62, O44, Q43, Q48

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1 Introduction

As global CO_2 emissions keep rising, economic instruments that aim at reducing fossil fuel use may have to reach high stringency levels (Allen et al., 2018). Typically, such instruments are not introduced unexpectedly but rather devised, debated, and announced beforehand (Gupta, 2010). The more demanding the policies are, the more impactful their credible announcements may become. The information about upcoming climate policies can help agents reallocate their resources optimally by the time the policy is enacted (Di Maria et al., 2012). The ability to take advantage of an announcement is not homogeneous across the population. Even though individuals might be given equal time and opportunity to adjust, their ability to do so depends on the amount of resources they own. Policy announcements may thereby induce a strong distributional impact and aggravate social inequality even before the actual implementation.

This paper examines the impact of the anticipation of a carbon tax on welfare inequality and economic growth. We use a numerical general equilibrium model, CITE (Bretschger et al., 2011), of a multi-sectoral economy with endogenous growth and heterogeneous households with a labor-leisure choice. We aggregate data from the Swiss input-output table (IOT) into 11 economic sectors and five household groups distinguished by their income and activity status. Data on the households come from the Household Budget Survey data (HABE) of the year 2014. We study the repercussions of the anticipation of the carbon tax of various stringency levels for the economy. First, we run the usual anticipation scenario where the policymaker announces the carbon tax before its actual implementation.[1] Second, we simulate an un-anticipation world where agents in the economy cannot adjust to the upcoming carbon tax—as if there were no prior announcements. The policy target (that is, the carbon emissions limit) is the same in both the anticipation and the un-anticipation cases. We then compare the results from the two scenarios and attribute the differences to the role of anticipation.

Our study is the first to analyze the effects of policy anticipation on economic growth and the welfare of heterogeneous households. It is critical to do so through the prism of endogenous growth. Recent studies emphasize the role of induced technological change in the effectiveness of climate policy (Bretschger et al., 2011; Acemoglu et al., 2012). In this case, advanced investment decisions redirect investments to innovation in low-carbon technologies (Bosetti et al., 2009). Technological progress and learning can thus

[1]We always treat a policy announcement as credible and do not consider the uncertainty of political decision-making.

counterbalance the adverse effects of policy anticipation (Di Maria and van der Werf, 2008; Nachtigall and Rübbelke, 2016). Our results suggest that the anticipation period, first of all, alters the investment decisions. The anticipation of carbon tax induces early divestment from fossil fuels. These decisions, in turn, impact the sectoral and aggregate growth, households' choices for labor supply, and the growth rates of consumption.

We find that advance policy announcement allows economic agents to align their investment decisions accordingly and lower the future costs of compliance with the policy. Yet, the extent to which individuals can benefit from early capital reallocation is not homogeneous and depends on their participation in the capital market. Individuals that own most of the capital in the economy and enjoy a high share of capital rents in their income (we call them *capitalists*) benefit from the investment reallocation the most. Other individuals who primarily rely on labor income and government transfers have to face the new market conditions and adjust their consumption and labor decisions. The presence of an anticipation period, therefore, has a regressive effect—regardless of the stringency of the policy target. In fact, the regressive effect of the anticipation deepens as the policy's stringency increases.

The paper also explores the impacts of stringent climate policies on the economy's path to decarbonization. We simulate carbon emissions policies that target CO_2 up to 95% reductions from its current level by 2050. We find that the stringency of the policy has a non-linear effect and impacts the anticipation dynamics not only quantitatively but also qualitatively. For a low enough carbon reduction target, households' consumption-smoothing dominates their consumption-investment decisions. When the policy's stringency goes beyond a certain point (around 50% of CO_2 emission reduction), capital reallocation dynamics come into play. Since the capital owners foresee the increase in the profitability of the "clean" technologies at the time of the policy's announcement, the anticipation allows them to adapt to the strict carbon targets. Under carbon reduction targets around 95%, anticipation has a positive impact on the welfare of all households. Because of the intrinsic inequality of the anticipation effect, capitalists benefit more from the adaptation opportunity than poorer households.

For low and mild carbon taxes, the anticipation decreases the welfare of all active households by about 0.2% over the whole 30 years of study. The same policies are neutral or even have a positive effect on the welfare of retired households. The welfare of the most wealthy of them (named "retired high") may increase up to 0.25% for an 80% carbon reduction policy. For the most stringent policy (95% of carbon reduction), the welfare increase of the "retired high" households is about 0.5% point higher than the "active low" (the least wealthy households of the working group) type of households .

At last, we look at a scenario where the redistribution to the households is inverse-proportional to their income level. This redistribution scheme is common in the carbon tax literature (see for example Beck et al., 2015) and aims to foster a progressive effect of the tax. We find that the anticipation of this policy undermines its purpose. The wealthier households anticipate lower tax revenues compared to a homogeneous lump-sum redistribution scheme. To counter-balance this loss, they reallocate even more of their capital amplifying the negative effects on the working group of households.

Related literature

A long series of macroeconomic studies underline the role of a policy's announcement on its total effect. Recent empirical analyses by Mertens and Ravn (2012) and Favero and Giavazzi (2012) provide evidence that anticipation effects contribute largely to business cycles in the U.S. They find pre-announced tax cuts give rise to contractions in output, investment, and hours worked before their implementation, whereas real wages increase. van der Wielen (2020) find similar results for the European Union. Mertens and Ravn (2011) confirm these empirical findings in a DSGE model. Our work differs from these ex-post analyses, in that we perform an ex-ante analysis of an environmental policy.

A large part of environmental economics considers the effect of the announcement of a policy through the prism of the green paradox (Sinn, 2008). The concept of green paradox applies when climate regulations have an effect that contradicts the intended one. Under resource scarcity, the regulation's announcement may induce more intensive extraction of fossil fuels instead of their conservation. Resource owners have an incentive to accelerate the extraction before the policy makes it costlier (Di Maria et al., 2012; Riekhof and Bröcker, 2017; Di Maria et al., 2017). Jensen et al. (2015) find that such adverse effects are even more likely when the policy's stringency increases steeply in time. Smulders et al. (2012) show that the green paradox may arise even without resource scarcity. The anticipation of a carbon tax might lead to an early increase in investments and capital accumulation accompanied by more intensive fossil energy use. In this case, the green paradox arises purely from the adjustments in consumption-investment decisions. The presence and strength of the green paradox effect depend on many factors, such as the extraction and adjustment costs for fossil energy and the availability of clean substitutes (van der Ploeg and Withagen, 2015). If fact, Baldwin et al. (2020) show that agents might choose to divest from carbon-intensive sectors early and thereby prevent stranding of assets under the policy.[2] As Bauer et al. (2018) and Okullo et al. (2020) suggest, the benefits from earlier and higher investments in clean energy technology might outweigh the incentives to turn to fossil fuels before the policy is enacted. Our analysis departs from the green paradox-divestment dilemma and explores the changes in welfare distribution and key macroeconomic variables driven by a policy announcement.[3]

Incorporating heterogeneous groups of households is a critical step towards a better understanding of the distributional effects of climate policies (Rao et al., 2017; Keppo et al., 2021). According to the early review by Wang et al. (2016), studies generally tend to suggest regressive effects, though the conclusions depend on the design of a policy. To investigate the equity effects, Rausch et al. (2011) thoroughly incorporate households' heterogeneity and find that revenue recycling scheme impacts both the efficiency and equity of a carbon policy. They suggest that the trade-off between the progressivity on the income side and the regressivity on the consumption side defines the outcome. Fremstad and Paul (2019) support this finding and suggest that lump-sum redistribution makes the tax progressive. Karydas and Zhang (2019) show that the progressivity is unlikely to hold under stringent policies. The recent meta-analysis in Ohlendorf et al. (2021) shows that studies are more likely to find regressive effects in developed countries and proportional or progressive effects in low-income countries. The inclusion of general equilibrium effects also plays an essential role for the results. Drawing on this background, our paper offers an insight into the distributional effects of the anticipation, as opposed to the implementation of a climate policy.

The rest of the paper is structured as follows. Section 2 presents the CITE model, its calibration, and major assumptions. Section 3 describes the policies and scenarios designed to isolate the anticipation effect. Section 4 presents the results for the total and disaggregated effects of policy anticipation for welfare and economic growth. Section 5 discusses the policy implications in a broader context. Section 6 concludes.

[2]In support of this claim, the literature suggests that investors timely adjust their expectations to future policies and take into account stranded assets risks (Vikash Ramiah et al., 2013; Sen and von Schickfus, 2020).

[3]The more general literature that juxtaposes "history" with expectations finds that it is not only the current state of the economy that determines its equilibrium path. Expectations about the future economy's state can also play an important role in determining an equilibrium (Krugman, 1991). Applications to environmental policy suggest that a policy may raise self-fulfilling "green" expectations and might even have to do so to shift the economy's trajectory towards energy transition (Bretschger and Schaefer, 2017; van der Meijden and Smulders, 2017; Schäfer and Stünzi, 2019)

2 Model and Methods

In this section, we outline the main features of our economic model. We describe the data used for calibration, the key modelling assumptions, and the computational strategy to solve the model.

2.1 Economic model

We use the CITE economic model of general equilibrium with endogenous growth developed by Bretschger et al. (2011). The growth mechanism in CITE is an extension of the increasing-variety model of Romer (1990) and includes energy use in the production of the intermediate good. This extension makes it possible to examine how the substitutability between labor and energy might affect economic growth when their relative prices change under various policies or other changes in economic conditions. CITE models a small open economy that consists of different regular, non-energy sectors of an economy and four energy-specific sectors—oil, gas, heat, and electricity. All sectors have similar structures of production that feature three levels: the production of the intermediate goods, the production of sector-specific intermediate composite, and that of the final good. We assume that knowledge is sector-specific and we do not consider international knowledge spillovers.[4] Below,we outline the main features of the model. Appendix A offers its rigorous presentation.

2.1.1 Production

For each sector i, the markets for final good (Y_i), intermediate composite good (Q_i), and labor in manufacturing and R&D (L_{X_i} and L_{J_i}) are perfectly competitive. Firms, however, can invest in physical (I_{P_i}) and non-physical (I_{N_i}) capital to invent new varieties of goods and enjoy profits from their monopolistic position. These new varieties constitute the capital (J_i) of the sector. The nesting of the model is such that the fossil fuels are combined with electricity first to produce the energy aggregate. This aggregate is nested with labor to produce intermediate goods, which then combine with capital to produce the intermediate composite. Our nesting of capital (K), labor (L) and energy (E) follows a $K - LE$ form.[5] The amount of accumulated capital (J_i) determines the number of

[4] For a use of CITE with international knowledge diffusion, see Bretschger et al. (2017).

[5] Models with exogenous growth are commonly specified in $KL - E$ form (Manne et al., 1995; Paltsev et al., 2005; Bosetti et al., 2006). In our endogenous growth framework, capital accumulation enhances the productivity of all other input factors, hence the $K - LE$ formulation. See Appendix A for more

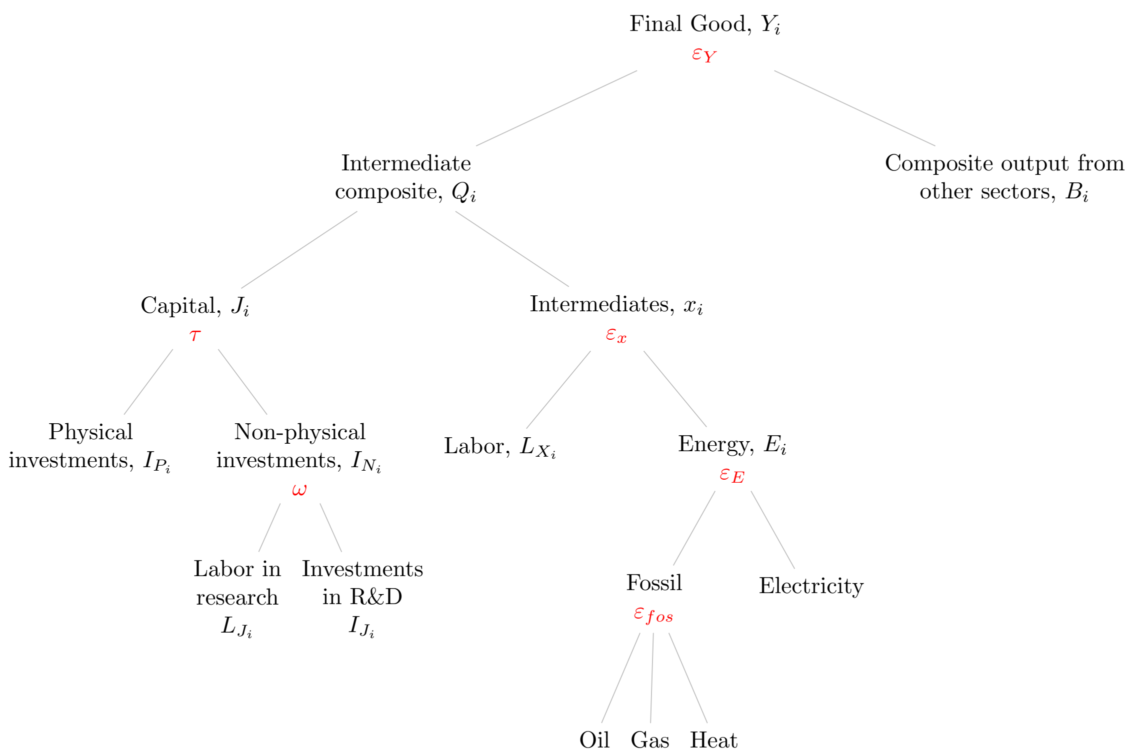


Figure 1: Sectoral production structure of the economy

varieties that comprise the intermediate composite Q_i. Figure 1 provides an overview of the production structure for each sector of the economy.

At any time t, the labor employed in research, L_{J_i}, and labor employed in the production of the intermediate goods, L_{X_i}, face the same wage w_t determined on the competitive market.

2.1.2 Consumption and welfare

Following the procedure in Karydas and Zhang (2019), we define five categories of households based on their income levels and activity status. All households maximize their utility from consumption and leisure. We proxy leisure with the complement of the labor force participation rate, taking the calibration from Karydas and Zhang (2019).[6] Figure 2 sketches consumption and welfare choices in the economy. The agents have perfect

details.

[6] Karydas and Zhang (2019) use data on income and labor force participation rate provided by the Swiss Federal Office of Statistics. They map the time endowment of the households between age groups and income groups for the following household categories (with their labor force participation rates given in brackets): Active low (0.15), Active mid (0.1), Active high (0.25), Retired low (0.9), Retired high (0.9).

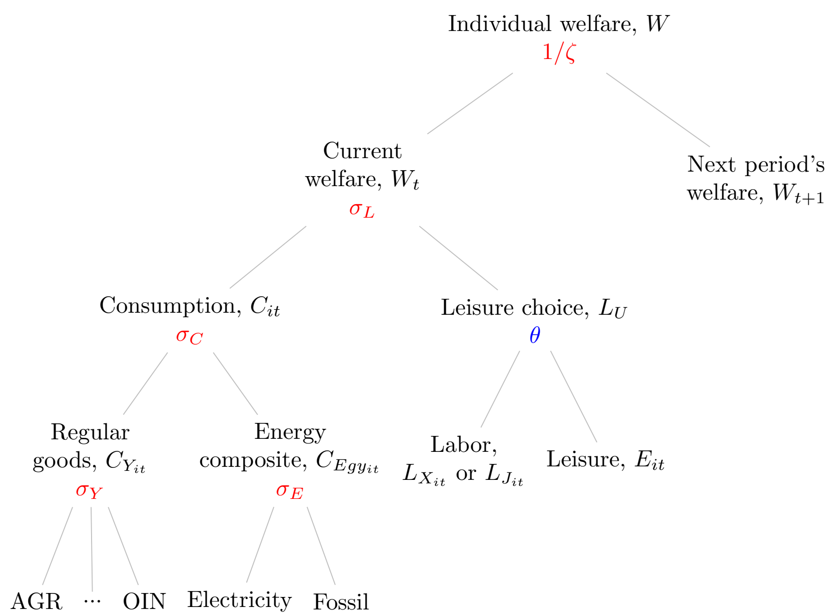


Figure 2: Welfare and demand structure of the economy

foresight and allocate their income between consumption and investment.

2.1.3 International trade

As CITE models a small open economy, international trade matters in the production. We follow the Armington approach (Armington, 1969) to model international trade. In the production process, we assume that in each sector domestically produced and imported goods are imperfect substitutes. At the level of the final good production, the goods from international trade are represented by the composite input B_i—which is an aggregate of Armington goods from all sectors. Once the final good is produced, it is divided between export and domestic consumption according to the exogenous foreign prices and under the constraint that trade is balanced in every period. The exported goods and the output produced for the home market are imperfect substitutes as well. Consumers, who purchase the final output, consume Armington aggregates—that is, combinations of domestic and foreign production.

2.1.4 Government

The model also includes a government, whose role is to collect and redistribute the pre-existing taxes (capital and labor taxes, subsidies, and tariffs), the new carbon tax, and transfers. The governmental budget is initially balanced and stays such throughout the analysis. In our main scenario, the government redistributes the revenues from the carbon tax in a lump-sum fashion.

2.2 Solving the model

To solve the model for the different policy scenarios, we first calibrate CITE to the balanced growth path (BGP). In this section, we describe the data and expose our main assumptions for the calibration to the BGP as well as our computational strategy to isolate the effect of anticipation.

2.2.1 Households and sectors data

We use the Swiss Input-Output Table (IOT), Energy Input-Output Table (EIOT), and the Household Budget Survey data (HABE) of the year 2014 (they are the latest data available) to construct the Social Accounting Matrix (SAM) for Switzerland.[7] We aggregate the 77 economic sectors of the IOT into the 11 sectors used in the study (see Table B.1 in Appendix B). The energy sector is further disaggregated into fossil (oil, gas, heat) and electricity sources following Bretschger et al. (2011). Because the electricity sector in Switzerland emits hardly any CO_2, we consider it a clean energy technology and an alternative to fossil fuels.

The HABE data contains information on 9'367 Swiss households summarized in Table 1. We aggregate these households into five categories based on their working status (active or retired) and level of net income (low, medium, or high for active households and low or high for retired households). After aggregating the households, and taking into account the number of people living in each household, we find that about 80% of the population is active, among which 44% is in the active-low group. The active-high and the retired income groups own most of the capital of the economy (62%). But the active-high receives about two times as much income from labor than from capital, whereas the two retired income groups rely to a large extent on their capital earnings. The numbers are comparable to those in Karydas and Zhang (2019). The calibration of the model takes into account the pre-existing taxes and subsidies of the Swiss economy.

[7] The data are provided by the Federal Statistical Office of Switzerland. Nathani et al. (2019) document the EIOT.

Category	Source
Income	Labor, Capital, Transfers
Spending	Consumption, Investments
Taxes	Income, Labor, Subsidies, Tariffs
Activity status	Active or Retired
Size	Number of people living in each household

Table 1: Description of the data on the 9'367 Swiss households

2.2.2 Key assumptions and the benchmark scenario

The economy is calibrated to follow the BGP with the growth rates that match those of the Swiss economy. We set the growth rate of the economy, g, to 1% per year—which follows from the average growth rate of GDP per capita in Switzerland in the last two decades.[8]

On the balanced growth path, all sectors grow at the same rate as the entire economy. The growth rate for capital, g_K, however, is different and derives from the expansion-in-variety mechanism of endogenous growth. It relates to the economy's growth rate as $g_K = g^{\kappa}$, where κ is the share of non-capital goods in production across all sectors. Based on the IOT data, we set the value for κ to 0.7, which implies the growth rate of capital equal to 0.7%. The annual rate of return on capital, r, takes the average value of the interest rate set by the Swiss National Bank. The average value for this interest rate over the last 20 years is 0.6%.[9]

Once the economy's growth rate and the interest rate are chosen, the discount rate is determined endogenously by the Keynes-Ramsey rule,

$$g = \left(\frac{1+r}{1+\rho} \frac{P_{C,t}}{P_{C,t+1}} \right)^{\frac{1}{\xi}}, \tag{1}$$

where $P_{C,t}$ is the price of consumption in period t and on the BGP it must hold that

[8] According to the World Bank Open Data, the 10- and 20-year average growth rates for GDP per capita in Switzerland are 1% and 1.03% correspondingly. The data can be retrieved from https://data.worldbank.org/indicator/NY.GDP.PCAP.KD.ZG?locations=CH.

[9] The current interest rate policy is published on the website of the Swiss National Bank at https://www.snb.ch/en/iabout/stat/statrep/id/current_interest_exchange_rates; the historical data can be retrieved from the Bank for International Settlements at https://www.bis.org/statistics/cbpol.htm.

$\frac{P_{C,t}}{P_{C,t+1}} = 1 + r$. The discount rate can thus be calculated from

$$\rho = \frac{(1+r)^2}{g_C^{\zeta}} - 1. \tag{2}$$

We assume the intertemporal elasticity of substitution, $1/\zeta$, equal to 0.85, which yields a rather conservative discount rate of 0.03%. The values for the remaining parameters used in calibration are listed in Table C.2 of Appendix C.

Finally, the numerical solution is an approximation of the theoretical model described in Appendix A using a finite number of periods. We employ the method from Lau et al. (2002) to solve for the infinite horizon equilibrium by imposing additional constraints for capital accumulation in the terminal period T. We fix the growth rate of investments in the terminal period to be equal to the output growth rate,

$$\frac{I_T}{I_{T-1}} = \frac{Y_T}{Y_{T-1}}. \tag{3}$$

That is, we impose a constraint on the growth rate of investments only. The actual growth rate of the economy and the terminal level of capital stock are free variables.

2.2.3 Computational strategy

The model's competitive equilibrium, given our initial SAM and calibration to the balanced growth path, follows from a vector of prices and quantities such that firms maximize their profits, consumers maximize their intertemporal utility according to their budget constraints, and the adjustment of the price mechanism clears all markets. We use the General Algebraic Modeling System (GAMS) software and the GAMS/MPSGE higher-level language (Rutherford, 1999) together with the PATH solver (Dirkse and Ferris, 1995) to solve the model as a mixed-complementarity problem.

3 Scenarios and analysis

In this section, we provide the details on the policy scenarios and the way we measure the effect of anticipation.

3.1 Policy scenarios

We implement policies linearly over the three decades from 2020 to 2050. For all policies, we set a target reduction in CO_2 emissions in proportion to their benchmark value in the first year of the business-as-usual (BAU) scenario. For example, a target of 90% reduction corresponds to a policy that aims at 90% less CO_2 emissions by 2050 in comparison to their level in 2020. We study policies with CO_2 emissions reduction targets from 1% to 95% from their benchmark level. The key object of our interest is the effect caused by the anticipation of these policies on the dynamics of the macroeconomic variables.

We focus on a carbon tax as the main policy instrument. The tax is paid by the economic sectors as well as final consumers according to the carbon intensity of their consumed energy. The tax is collected by the government and redistributed lump-sum to households. The results of this redistribution are later compared to two alternative ways to recycle the tax income. First, the revenue is used in an attempt to alleviate the income inequality across the different income groups of households. In this case, the redistribution is inversely proportional to the level of household income. Second, the revenue from the carbon tax is directed to stimulate research in all sectors and thereby facilitate the overall economic growth.

3.2 Design of the anticipation effect

We study the effect of anticipation by comparing two different cases of policy implementation. In the first, anticipation case, the policy is announced already in 2020 and scheduled for implementation starting in 2030. In the second, un-anticipation case, the policy is not announced until its implementation in 2030, and thus no adjustments from economic agents are possible beforehand. The differences in macroeconomic dynamics between the two cases then represent the effect of anticipating the policy.[10]

More formally, to obtain the effect of anticipation on a given economic variable X (for example, X can represent welfare, GDP, or wages), we compute the difference between the values that X takes under the two implementation schemes. Under the anticipation scheme, at time t_0 the policymaker announces a climate policy to be implemented at time t_1. Agents can thus adjust their optimal choices before the implementation. We call

[10]What we call the anticipation period is sometimes called a "phase-in" in the literature (Williams III, 2011). We choose not to use this term in order not to confuse the reader. Most studies use it to refer to a policy that is already implemented but set to gradually become more stringent. In our case, the policy is enacted later than it is announced.

the optimal path of X under anticipation X_A. Under the un-anticipation scheme, the policymaker does not announce the coming climate policy at t_0 but rather implements it right away at time t_1. Since the agents do not know about the policy in advance, they cannot prepare for the coming regulation at time t_0 and adjust their behavior only at t_1. We call the optimal path of X under un-anticipation X_U. The effect of anticipation, Δ_X^A, is the difference between the two optimal paths of X under the two schemes,

$$\Delta_X^A = X_A - X_U. \tag{4}$$

In practice, to obtain the un-anticipated path X_U, the agents' choices at time t_0 are fixed to their benchmark values (as these values are optimal in the absence of policy). It is only from time t_1 onward that the optimal allocations can deviate from the BAU to comply with the policy.[11]

4 Results

This section presents the main results of our analysis. First, we state the general effects of policies of different stringency levels. Second, we highlight the anticipation effect of these policies on welfare distribution and economic growth. The objective is not to propose optimal policies, but rather to show the impact of policy announcement on the production side and on the consumption side of the economy.

4.1 General effects on aggregate economic variables

Carbon policies of any stringency slow down the economic growth—at least in the first two decades. Figure 3 shows the decadal growth of the aggregate output under the implemented policies and agents' full anticipation.[12] In most cases, the growth rates lie below the benchmark level of 1%. At the same time, they hardly ever fall below 0.9%, which indicates slightly slower yet persistent growth. For mild policies (that is, policies that aim at 20% to 50% reduction in CO_2 emissions), higher emission reduction targets directly correspond to a gradual deceleration of the economic growth. Under more stringent policies, the economy mobilizes more of its resources to stimulate the production of final goods.

[11] Note that the values of a variable in the two implementation schemes can differ also in the later periods $t_i, i > 1$. The anticipation effect refers to the deviations in the optimal paths both before and under the policy in comparison to the un-anticipation path.

[12] For both the supply and demand sides of the economy, we first present the overall impact of the policies. The anticipation effect is isolated in subsequent figures.

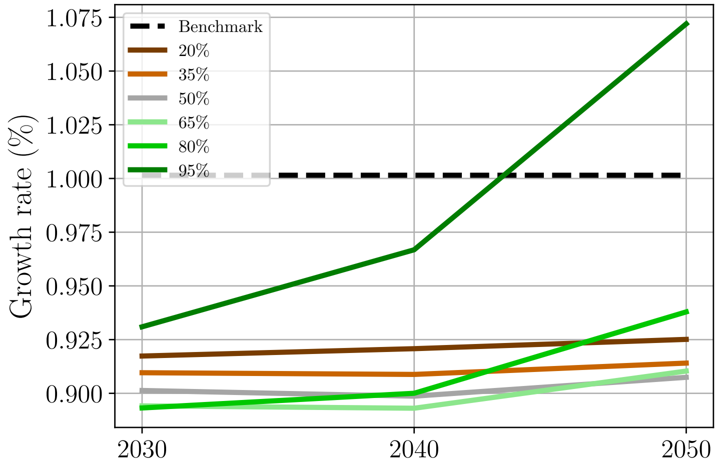


Figure 3: The effect of carbon policies on the aggregate output growth. The figure shows the results for various policy targets under full anticipation of future policies. For example, a 65% policy implies a 65% reduction in CO_2 emissions in comparison to the benchmark year.

Therefore, even with a low start, the growth rate tends to have an increasing profile and under the 95%-reduction policy reaches 1.075% in 2050.

This overall effect on output growth derives from consumption and investment dynamics. All implemented carbon reductions hamper the growth of consumption—in the most extreme case, the growth rate falls below 0.8%.[13] Under moderate emissions reductions, the aggregate investment grows slightly slower too. When the economy has to cut the emissions drastically, the aggregate economic growth requires both higher levels and steeper profiles of investments. Their growth rate eventually surpasses the benchmark level—drawing even more resources away from consumption.

Just like the general effect of policy implementation, the anticipation effect on the total output is more pronounced the stricter the policy. As shown in Figure 4, the output is higher in the first period if the agents know that a carbon regulation is coming in the next period. In the case of less stringent policies, the anticipation shifts the production profile towards the earlier periods—the output volumes are higher in the first decade and notably lower in the later decades. Under the most ambitious policy, knowledge about the upcoming regulation ensures higher levels of final production in the first three decades of the modeled period, with the maximal difference of 0.3% in 2020.

Figure 5 sheds more light on this dynamics by displaying the effects of anticipation on

[13]See the Figure D.1 in the Appendix.

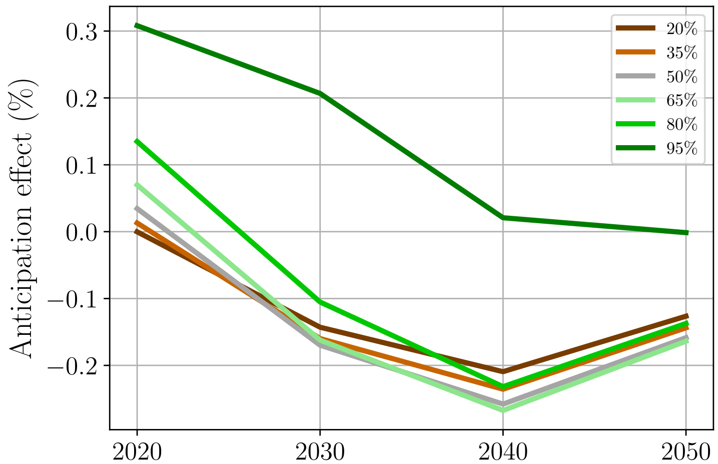
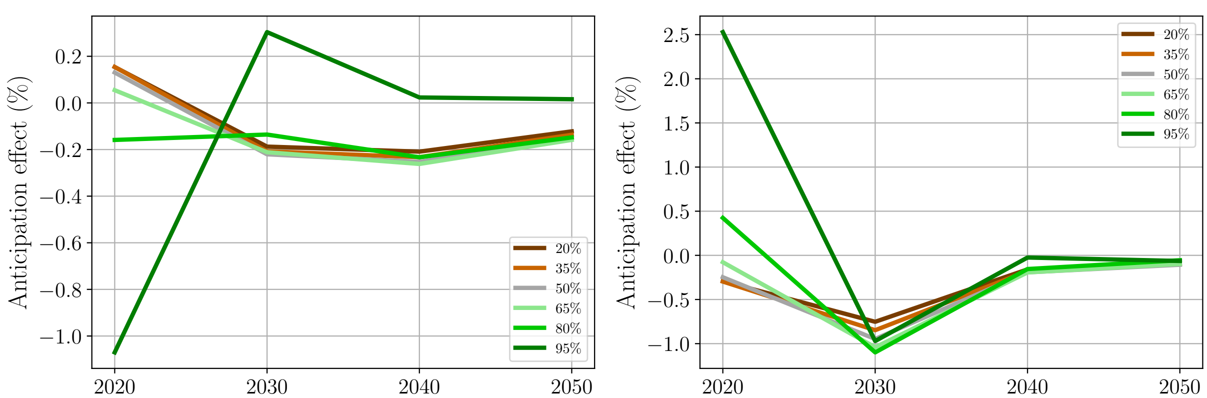


Figure 4: The effect of anticipation on the aggregate output. The figure shows the effect of anticipation for various policy targets. A 65% policy implies a 65% reduction in CO_2 emissions in comparison to the benchmark year. The anticipation effect represents the difference in aggregate output between a scenario where agents can anticipate in 2020 a policy to be implemented in 2030 and a scenario where they can observe the policy only in 2030. A positive effect means that the aggregate output is higher in the anticipation case.



(a) Consumption **(b)** Investment

Figure 5: The effect of anticipation on the aggregate consumption and investment. The figure shows the effect of anticipation for various policy targets. A 65% policy implies a 65% reduction in CO_2 emissions in comparison to the benchmark year.

the aggregate levels of consumption (left panel) and investment (right panel). Informed about an upcoming mild policy, the agents shift their consumption in time such that more goods can be consumed beforehand—at the expense of the later consumption subject to the carbon taxation.[14] As a result, less resources are invested in sectoral growth. Under stringent policies, however, the opposite effect dominates as households tend to reduce their consumption in the first period in favor of increasing the investments in the economy. These additional investments ensure that the distribution of capital in the economy can start adjusting to a new optimum beforehand. Under the most stringent policy, the initial forgone consumption of over 1% of the total consumption allows the households to consume more in the later periods.

Sectoral impacts

The impacts of carbon taxation are highly asymmetric across the economic sectors. In general, the policies favor the sectors with lower carbon intensity and higher substitution possibilities. The sectors that strongly rely on fossil energy, on the other hand, are left at a disadvantage. Even before the actual policy implementation, the consumption of fossil fuels falls (see Figure E.2 in the Appendix).

Figure 6 shows these diverse sectoral effects on the example of the most stringent policy that aims at 95% emissions reduction, under full anticipation. The sector with the highest energy-intensity—transport—is hit by this policy the strongest and loses over a quarter of its benchmark level of output by 2050. Less carbon-intensive sectors—such as the agriculture and the chemical sector—end up benefiting from the policy. Their corresponding levels of output rise by 32% and 24% by the end of the modeled period. The industries classified as "other" increase their output level by almost 70% by the time the policy target is reached.

The isolation of the effect of the anticipation period reveals more sophisticated dynamics. Figure 7 provides three demonstrative examples of the effects of anticipation on the sectoral investments and capital accumulation under the policies with increasing targets. One intuitive example of such effects is provided by the banking sector (panel **(a)** of Figure 7). Knowing about the upcoming policy and its positive impact on the banking sector, investors choose to reallocate a part of their resources to this sector in advance—hence the positive anticipation effect on the investment in 2020. Consequently, much less of such

[14]Note that, if higher consumption implied proportionally higher dirty energy use, the green paradox could occur here. But, thanks to advance substitution towards clean energy, the amount of dirty inputs does not increase with higher consumption.

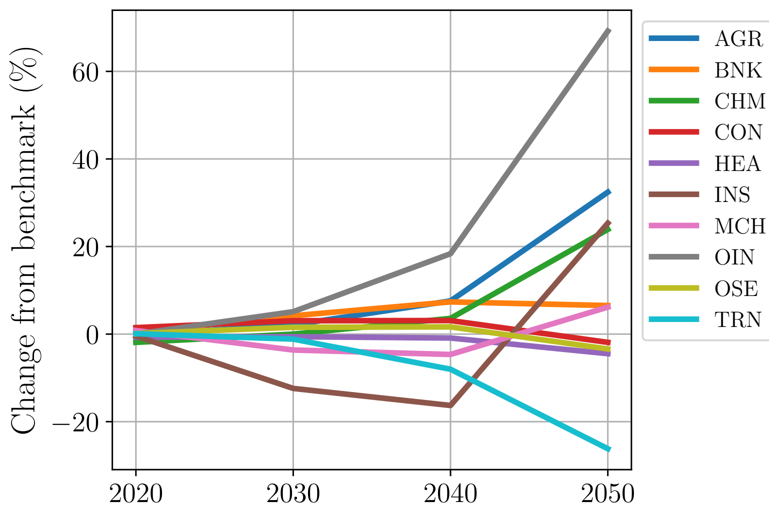
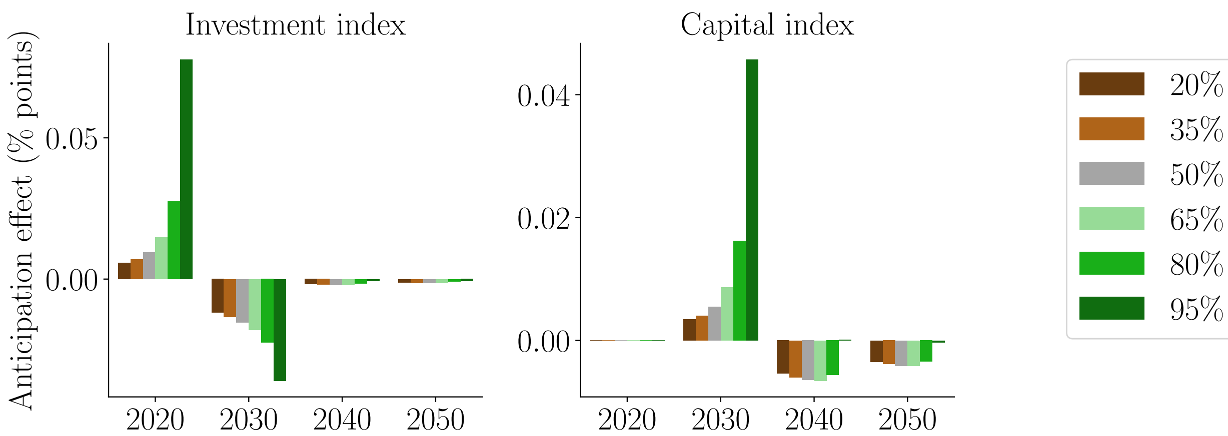


Figure 6: The effect of 95%-reduction policy on the sectoral output. The figure shows the results under the anticipation of the policy.

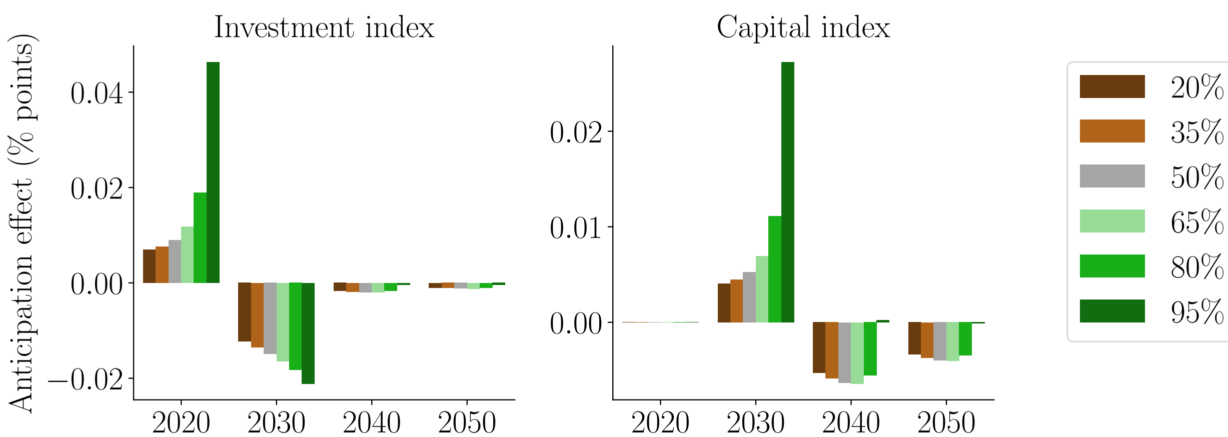
reallocation takes place in the second period—hence the negative anticipation effect on the investment in 2030. By this time, in the case of anticipation, the additional early investment is already transformed into a higher level of capital—hence the positive anticipation effect on capital in 2030.

The fact that the transport sector has a similar effect of anticipation (panel **(b)** of Figure 7) at first seems less intuitive. This sector is energy-intensive and heavily burdened by carbon taxation. Yet, in anticipation of such a policy, the investors decide to stimulate this sector, too, with additional investments. The reason for such reaction becomes clear when we take into consideration the cross-sectoral structure of the demand in the economy. The transport sector enjoys relatively high demand from all other sectors, especially those that grow faster under the policy. To maintain the production level such that it meets the demand, the investment made in advance promotes the substitution of capital for energy in this sector. Advance anticipation therefore to a certain extent alleviates the negative effect of a carbon tax for this sector.

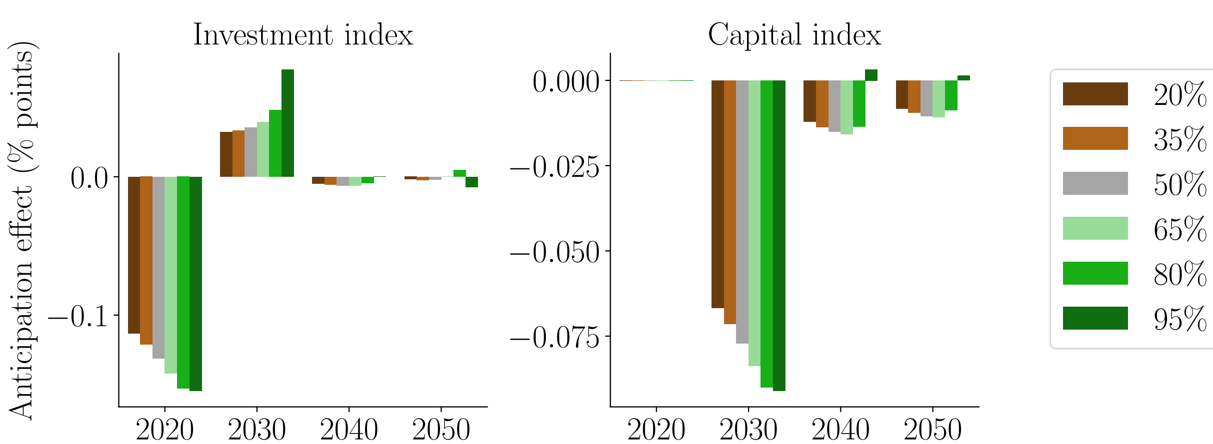
The insurance sector is an example of a completely opposite effect of anticipation (panel **(c)** of Figure 7). Under the stringent carbon policies, the growth of this sector slows down initially and accelerates only in the last modeled decade. The demand from the other sectors for its products is also relatively low—both in the benchmark scenario and under the policies. The sector thus witnesses a divestment already in the first period if the investors anticipate a carbon tax—hence the negative anticipation effect on the investment



(a) Banking sector



(b) Transport sector



(c) Insurance sector

Figure 7: The effect of anticipation on the investment and capital accumulation in the banking sector, the transport sector, and the insurance sector

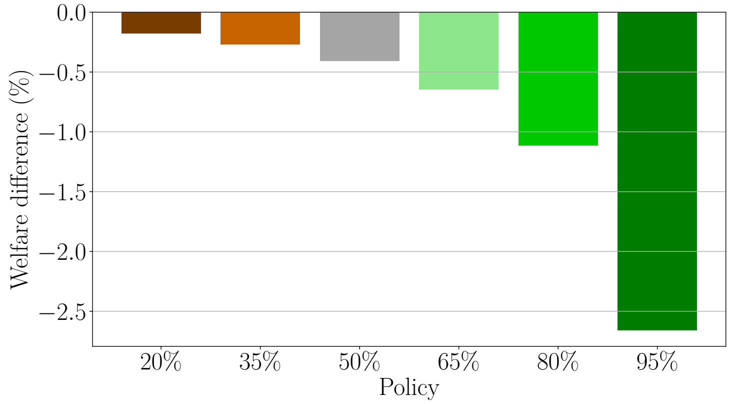


Figure 8: The effect of carbon taxation on the aggregate welfare. The figure shows the effect of the carbon tax on aggregate welfare for various policy targets. The y-axis represents the welfare difference between the business-as-usual scenario and the policy scenario under full anticipation. A 65% policy implies a 65% reduction in CO_2 emissions in comparison to the benchmark year.

in 2020, which transfers into a lower capital level in 2030. Without such anticipation, this reaction is triggered directly by the implementation of the policy in the second period.

4.2 Welfare effects

The aggregate welfare reflects the utility that the households enjoy from both their consumption and leisure. Carbon taxation of any stringency lower this welfare by imposing an additional tax distortion on the economy. Figure 8 shows the highly nonlinear magnitude of such losses with respect to the policies' stringency. For example, a policy that aims at a 50% reduction in CO_2 emissions is associated with a loss of welfare of around 0.5%, whereas further reductions to 80% and 95% correspond to roughly two- and a five-fold increase in this cost. These results are consistent with earlier studies (Karydas and Zhang, 2019; Landis et al., 2019) and additionally include policy targets up to almost full decarbonization.

The effect of anticipation on welfare can be positive or negative as shown in Figure 9. With policy targets becoming more stringent, the anticipation effect changes from clearly negative to strongly positive starting from 90% reduction in CO_2 emissions. The anticipation effect on aggregate welfare spans from -0.08% to over 0.11%. At first sight, it appears that anticipating the coming carbon tax improves the aggregate welfare under stringent policies and harms it otherwise. To better understand the forces that drive such a difference, the dynamics of the anticipation effect have to be explored in more detail.

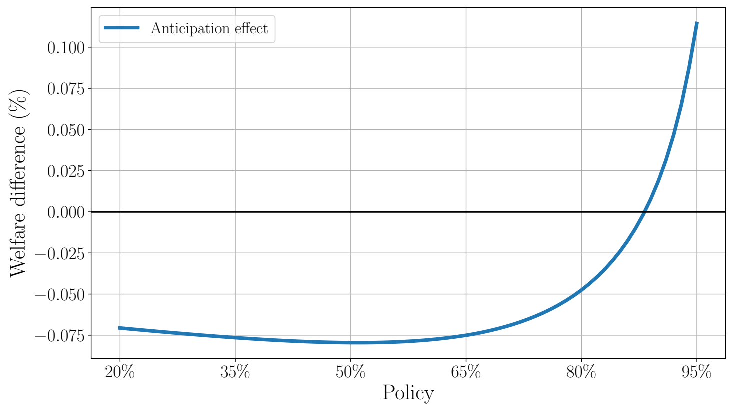


Figure 9: The effect of anticipation on the aggregate welfare. As the graph reads, the welfare difference between the anticipation and the un-anticipation scenario is about -0.05% of the benchmark welfare level for a 80% carbon reduction policy. This difference is due to the effect of anticipating the policy. A 80% policy implies a 80% reduction in CO_2 emissions in comparison to the benchmark year.

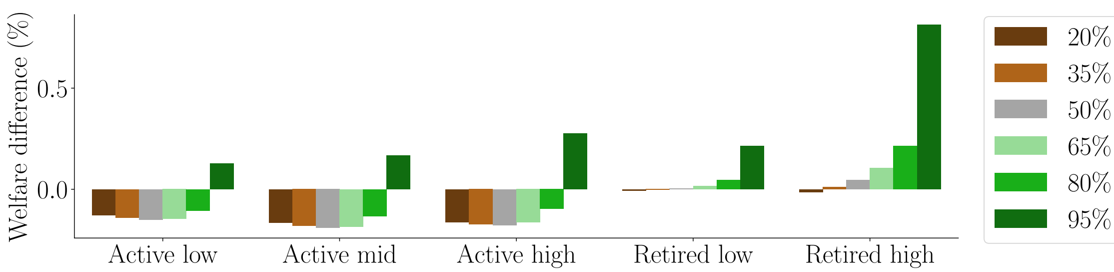


Figure 10: The effect of anticipation on welfare across the five groups of households. We show the results for scenarios that go from 20% to 95% reduction of carbon emissions. As the graph reads, the welfare difference for the "Retired high" household group between the anticipation and the un-anticipation scenario is about 0.8% of the benchmark welfare level for a 95% carbon reduction policy. This difference is due to the anticipation of the policy.

First, a closer look at the distributional effect of anticipation in Figure 10 reveals that the negative impact entirely relates to the working groups of households (named *Active low*, *Active mid*, and *Active high* in the figure). For these households, labor is the major source of income. In an anticipation of a carbon tax, the households expect the prices for energy and energy-intensive goods to raise. That is, they anticipate a loss of consumption. Thus, inline with consumption smoothing, they decrease their consumption before the actual imposition of the tax burden.[15] On the supply side, the anticipation of the policy implies a shift toward labor-intensive goods.[16] For the working households that corresponds to higher levels of labor supply and less leisure. This higher labor supply at the same time ensures higher output levels in the first period, as the additional labor mostly flows to production and not to research. The lower leisure levels, together with the lower levels of consumption, lead to a negative aggregate welfare effect.

The households' budget constraint allows us to better understand the mechanisms at stake. At any period of time, households face the following constraint from equation (A.3) in the model description (Appendix A):

$$\sum_i p^J_{i,t+1} J_{i,t+1} = w_t(L_{X_t} + L_{J_t}) + \sum_i (1 + r_t) p^J_{i,t} J_{i,t} - p^C_t C_t - T_t. \tag{5}$$

The left-hand side of the equation represents the value of the households' asset in sector i at time $t + 1$. In equilibrium, it is equal to the households' income from their work (w_t), either in research (L_J) or in the production of the final good (L_X), plus rents from their assets at time t, minus their consumption C_t at price p^C_t, and the net transfers T. When the households learn about the upcoming policies, they immediately adjust the future value of their assets $\sum_i p^J_{i,t+1} J_{i,t+1}$. The value of the "green" capital increases and the value of the "dirty" capital decreases. Since, in the economy, most of the sectors are in the "grey" area (that is, they require both clean and dirty energy as inputs), mild policies are not enough to incentivize a large reallocation of capital to clean technologies. The investors can anticipate the value of their assets to decrease. They compensate the excess of capital subject to the future tax by investing less than they would have without policy announcement (see Figure 5). Because, in this economy, production and research activities compete for resources, lower investments translate into higher output in the same period. Sectors already start to rely more on labor for their production. The rents households

[15] Appendix F provides the figures for the decomposition of consumption and labor supply across the households' groups.

[16] The literature documents this effect well (Williams III, 2016).

receive from their assets at time $t = 0$ and the net taxes they pay are given and cannot adjust.

The extra-supply of labor in $t = 0$ goes hand in hand with a decrease in leisure. The welfare impact of the loss of leisure, on the one hand, and the decrease in consumption, on the other hand, is clearly negative. The retired households suffer less from these mechanisms since, by definition, they work much less. In the anticipation scenario, they also enjoy the possibility to reallocate their investments earlier. Since their investment also decreases, they have spare resources. The retired households are the only ones to enjoy an increase in consumption in the first period.

In the anticipation scenario, the lower level of investment at the time of the announcement induces a lower level of capital at time $t = 1$. Households have fewer resources to allocate to the production of the final good or to reinvestment. Because capital owners pay lower carbon taxes if they can anticipate a policy, the overall level of taxes to redistribute is lower. In this case, households that do not own much capital not only consume less but also receive less lump-sum transfers from the redistribution. The regressive effect of the anticipation of the policy is clear.

As the policies become more stringent, the investment reallocations become more and more important. High carbon taxes lower the expected returns on dirty capital enough to trigger large redistribution of the investments—and subsequently capital—from carbon-intensive sectors to "cleaner" sectors with lower tax burden and higher profitability. This redistribution adjusts the production side of the economy to the upcoming carbon tax. For the working group of households, the mechanisms already at place for mild policies do not change; they even amplify. These households have to supply more labor and forgo more of their consumption during the period of anticipation. Capitalists, however, can earn notably higher returns on investment if they anticipate a stringent carbon tax. Given that capital returns comprise a large share of income for the richer and retired households, the anticipation effect is highly regressive.

All in all, the economy has a higher capital stock than it would have in the unanticipated scenario and all households can earn more capital rents. Also, the redistributed tax revenues are higher than in the mild-policy scenarios. This welfare benefit for the poorer households can partly offset their initial loss of consumption. Even though the anticipation of strict carbon policies has regressive effects, it increases the welfare of all household groups.

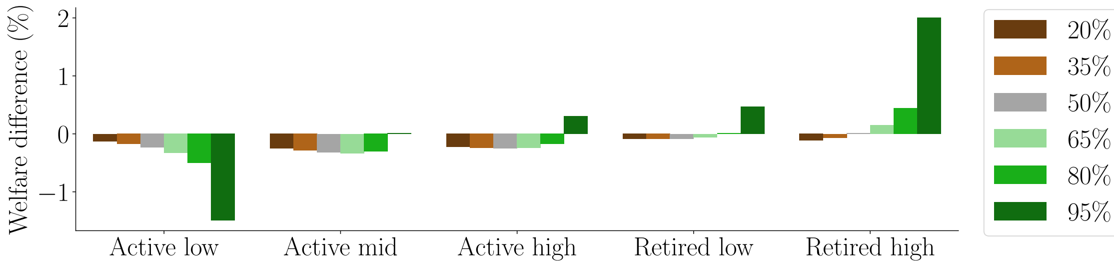


Figure 11: The effect of anticipation on welfare across the five groups of households under inverse-proportional redistribution scheme. We show the results for scenarios that go from 20% to 95% reduction of carbon emissions.

4.3 Redistribution inverse-proportional to income

As we show in Section 4.2, stringent policies might turn out disadvantageous for less affluent households. We explore this result for an alternative revenue recycling scheme that distributes tax revenues in the inverse proportion to the households' income level. In its naïve interpretation, such a scheme should utilize the tax revenues to reduce income inequality across the households.

Figure 11 shows that the anticipation effect for policies with the inverse-proportional redistribution scheme is comparable from that in the case of lump-sum redistribution for mild policies (around 0.1–0.3% of welfare loss for the working groups of households in mild policies). Yet, in anticipation of a stringent policy, capital owners adapt their investment decisions even more intensely. They reallocate more capital to cleaner sectors and thereby secure higher consumption levels despite their lower income from tax redistribution. The overall anticipation effect of the strict policies therefore stays regressive.

This dynamics becomes even more evident when we consider the absolute effects of the carbon taxation.[17] The rich households end up with a higher welfare under all policy targets. For a 95% carbon reduction policy, the welfare of the "Retired high" household group increases by about 7.5% when the tax revenues are redistributed inversely proportional to total income compared to the lump-sum redistribution scheme. The inverse-proportional reallocation scheme can thus benefit the richer groups of households and leave the poorer groups at a disadvantage.

[17]Figure G.5 in Appendix G shows the difference in absolute welfare impacts between the policies with inverse-proportional and lump-sum redistribution schemes.

5 Discussion

We find that under lump-sum redistribution of the tax revenues, the prior announcement of the carbon tax has regressive effects. We also show that this regressive effect of the anticipation period is even more pronounced under policy schemes that try to alleviate the regressivity of the tax itself. These alternative redistribution schemes might successfully turn a carbon tax to be progressive.[18] But our results aim at highlighting the welfare effect of the anticipation period and not the overall effect of the tax after its implementation. The anticipation period has regressive effects because of the *ex-ante* economic adjustments (e.g. capital re-allocation), although the tax and the redistribution of its revenues are not yet in place.

The regressive anticipation effect we find is an issue to be addressed. Yet, we do not advocate hiding or hindering the political process that leads to the adoption of the tax. The textbook un-anticipated implementation of a carbon tax is practically impossible. More likely, some scarce and asymmetric information of the upcoming "surprise" policy could influence the agents' expectations and contribute to economic inequality even stronger. A less transparent mechanism of political decision-making would favor those who are better informed about the upcoming policies. The policymaker ought to keep the democratic process and the political decisions that result from it transparent. Without this transparency, agents might have less trust in the government. Among other issues, the lack of transparency can increase uncertainty and slow down economic growth (Bosetti and Victor, 2011; Koch et al., 2016; Nemet et al., 2017). Besides, the results suggest that the overall anticipation effect of a carbon tax might be beneficial for the economy—provided that these benefits are distributed evenly across the society.

The policymaker might consider several tools to tackle the effects of the anticipation period. We show that the carbon tax is regressive in part because of the increase in profits that benefits the capital owners. First, the state could choose to increase capital taxation. The increase could be either permanent or temporary during the time of the anticipation period and until the redistribution of the carbon tax revenues kicks in. Second, the state could change the allocation of the capital share of a company between the workers and the owners. As Piketty (2020) suggests, the workers should be entitled to take part in the decision process of the company. Workers would also receive a minimum share of the company's dividend. This way, the reallocation of capital and the increase in profits in the "clean" sectors would also benefit the workers. Third, at the time it announces the

[18] See for example Beck et al. (2015) for the case of British Columbia's revenue-neutral carbon tax.

implementation of the tax, it may consider organizing training programs. Such programs would aim at providing workers with the new competencies they need to better adjust to the capital re-allocation that occurs in the economy.

One known limitation of the analysis of stringent climate policies is the models' limited ability to reflect the economy's transition to deep decarbonization targets (Pye et al., 2021). Studying the policies that almost eliminate CO_2 emissions by the mid-century comes at a price of making strong assumptions on the future technological frontiers. To address this concern, modelers ensure that their calibrations match the latest data and adequately include the substitution possibilities. The results also depend on the inclusion of mechanisms for energy transition and efficiency improvement.

In our analysis, we assume no mechanisms of energy efficiency improvement in the business-as-usual scenario. The economy is initially calibrated to follow a balanced growth path, such that the producers have no incentives to improve energy efficiency unless a policy pushes the production away from dirty energy. This makes our results immune to the rightful critique on the uncertainty of the extent of technological progress in the business-as-usual scenario. We also do not assume any carbon capture and storage (CCS) or negative emissions technology (NET), neither in BAU nor under the policies. Even though NET can arguably be a viable solution for eliminating residual emissions, we depart from this concept and focus on the absolute emissions reductions.

Under these rather conservative assumptions, we interpret the results of our scenarios as the upper bounds of the impact of a CO_2 policy on welfare. Besides, we use an updated estimate of the elasticity of substitution between clean and dirty energy (set to 2) based on the recent results from the empirical literature (Papageorgiou et al., 2017; Jo, 2020). This estimate reflects the latest technological advances that make dirty and clean energy better substitutes. A good substitutability between clean and dirty technologies alleviates the negative effect that CO_2-reduction policies have on welfare. It also allows the economy to reach ambitious policy targets that almost eliminate CO_2 emissions.

6 Conclusion

We study the role of the anticipation period of climate policies in a numerical model of general equilibrium with endogenous growth, heterogeneous households with labor-leisure choice, and multiple economic sectors. The anticipation period is defined as the time the policymaker gives to the agents in the economy to adjust their decisions before the implementation of a policy.

On an example of the Swiss economy, we analyze the implications of such an anticipation period for welfare and economic growth at various stringency levels of carbon tax. We find that both the magnitude and sign of the effect of policy anticipation may vary depending on the strength of the underlying economic incentives. Under moderate policy targets, the incentive to increase immediate consumption dominates and renders the aggregate welfare effect negative. In anticipation of more stringent carbon policies, the agents more actively redistribute their investments beforehand and achieve a more profitable allocation under the upcoming policies. Thus, the given opportunity to adjust in advance turns out beneficial on the aggregate level.

An equally important result is that the knowledge about future policies can have an unequal effect on different groups of households and can amplify the existing income inequality. The households' sources of income determine their ability to prepare and adapt to the upcoming taxation. The dynamics of the economy in anticipation of a carbon tax might change the economic environment against the working and poorer households, who might find themselves working more in an attempt to maintain their consumption level. For the richer and retired groups, on the contrary, additional capital earnings due to advance adjustments of their investment strategies partially offset the tax burden. The redistribution of the tax revenues directly to the consumers does not alleviate these disparities. Even distributing higher shares of tax revenues to the less affluent households does not change these dynamics—instead, it reinforces the advance adjustments to the policies.

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Appendices

A The CITE model

The version of CITE we use for our analysis is a dynamic, multi-sectoral numerical general equilibrium model of a small open economy where the growth mechanism follows Romer (1990).[19] Hence, the growth rate of the economy is determined by the expansion in the variety of intermediate goods. The broader variety of intermediate inputs increases productivity through gains from specialization. In addition to the main endogenous growth structure, it includes an energy sector. The time horizon of the theoretical model formulation is infinite but solved for a finite number of periods and goods in the numerical implementation.[20]

A.1 Household

We consider five infinitely lived, forward-looking households with perfect foresight and preferences:

$$U_h = \sum_{t=0}^{\infty} \left[\frac{1}{1+\rho}\right]^t \frac{\left(C_{h,t} + \theta_h L_{U_{h,t}}\right)^{1-\zeta} - 1}{1-\zeta}, \tag{A.1}$$

where $C_{h,t}$ is the consumption flow at time t by household h and L_U the leisure time. Each household is representative of an income and activity category.[21] Instantaneous utility from consumption and leisure is discounted at the intertemporal discount rate ρ and $\zeta \geq 0$ is the intertemporal elasticity of substitution. We consider no population growth and normalize total labor supply to unity. Each representative household allocate its time budget between manufacturing, research , and leisure. The time allocated to leisure, θ_h, is fixed and specific to each household category. Labor market clears:[22]

$$L_U + L_{X_t} + L_{J_t} = 1. \tag{A.2}$$

We also assume that the representative households own all the assets in this economy. Hence, they balance their income between consumption and saving for investment. Their

[19] Bretschger et al. (2011) and Karydas and Zhang (2019) use similar version of CITE.
[20] See Section C for a calibration to the balanced growth path.
[21] More details on households categories in Section 2.2.1.
[22] From now on we ignore the household index when no confusion arises.

total income consists of labor and capital income, and transfers from the government. Their expenditures are consumption expenses, tax payments, and investment:

$$\sum_i p^J_{i,t+1} J_{i,t+1} = w_t(L_{X_t} + L_{J_t}) + \sum_i (1+r_t) p^J_{i,t} J_{i,t} - p^C_t C_t - T_t. \tag{A.3}$$

Through intermediate firm ownership, household own the capital J_i from sector i, r_t is the interest rate, w_t is the wage from labor, T_t are the taxes and p^C_t is the price index of aggregate consumption such that $C_t = \sum_i C_{i,t}$ according to a CES aggregation of final goods as given by:

$$C_{i,t} = \left[\sum_i \alpha_C C_{Yi,t}^{\frac{\varepsilon_C - 1}{\varepsilon_C}} + (1-\alpha_C) C_{Egyi,t}^{\frac{\varepsilon_C - 1}{\varepsilon_C}} \right]^{\frac{\varepsilon_C}{\varepsilon_C - 1}}. \tag{A.4}$$

Both consumption of regular goods, $C_{Yi,t}$, and consumption of the energy composite, $C_{Egyi,t}$, also stem from CES production function with elasticities σ_Y and σ_E respectively as we describe in Figure 2. Maximizing (A.1) with respect to (A.3) gives the optimal consumption growth rate $g = \frac{C_{t+1}}{C_t}$ according to the standard Keynes-Ramsey rule:

$$g_C \equiv \left[\frac{1 + r_{t+1}}{1+\rho} \frac{p^C_t}{p^C_{t+1}} \right]^{\frac{1}{\theta}}. \tag{A.5}$$

According to Equation (A.5), a higher interest rate r boosts growth by inducing more savings, whereas a higher discount rate ρ gives incentives to present consumption, therefore reducing the growth rate.

A.2 Production

Final good producers

The representative final good producer in sector i and time t produces an output of $Y_{i,t}$ according to the following constant elasticity of substitution (CES) production function:

$$Y_{i,t} = \left[\alpha_Y Q_{i,t}^{\frac{\varepsilon_Y - 1}{\varepsilon_Y}} + (1-\alpha_Y) B_{i,t}^{\frac{\varepsilon_Y - 1}{\varepsilon_Y}} \right]^{\frac{\varepsilon_Y}{\varepsilon_Y - 1}}, \tag{A.6}$$

where $Q_{i,t}$ is the sector-specific composite of intermediate goods. $B_{i,t}$ denotes the composite output of final goods from all sectors that are needed as inputs for producing i. Outputs from different sectors are assembled into B according to a Leontief-type production function. The value shares of $Q_{i,t}$ and $B_{i,t}$ in the production function are determined by share parameters α_Y, and the elasticity of substitution between the two types of inputs are given by ε_Y. Both parameters are also sector-specific. The parameter values used in the numerical simulations are available in the Appendix C.

In each sector, the final good producer maximizes profits in a perfectly competitive market according to:

$$\max_{Q_{i,t},B_{i,t}} p^Y_{i,t} Y_{i,t} - p^Q_{i,t} Q_{i,t} - p^B_{i,t} B_{i,t}, \text{ w.r.t (A.6)}, \tag{A.7}$$

where $p^Y_{i,t}, p^Q_{i,t}$ and $p^B_{i,t}$ denote the prices of final goods, intermediate composite, and other inputs, respectively. Solving equation (A.7), and combining the resulting optimal demand functions for $Q_{i,t}$ and $B_{i,t}$ yields the following condition for optimal input use:

$$\frac{Q_{i,t}}{B_{i,t}} = \left(\frac{\alpha_Y}{1-\alpha_Y}\right)^{\varepsilon_Y} \left(\frac{p^B_{i,t}}{p^Q_{i,t}}\right)^{\varepsilon_Y}. \tag{A.8}$$

According to equation (A.8), an increase in the price of one input type increases the share of the other input in the optimal bundle.

Production of intermediate composites

In the second step of the production nest, producers of a sector-specific intermediate composite assemble their output $Q_{i,t}$ by combining different varieties of individual intermediate goods according to a standard Dixit-Stiglitz CES production function:

$$Q_{i,t} = \left[\int_{j=0}^{J_{i,t}} x^{\kappa}_{j,i,t} dj\right]^{\frac{1}{\kappa}}, \tag{A.9}$$

where $x_{j,i,t}$ denotes the j^{th} type of intermediate good variety that is available in sector i. $J_{i,t}$ is the sector-specific number of variety. This specification gives us two channels through which the intermediate sector can induce growth in the overall economy: either by producing a larger amount of any single variety $x_{j,i,t}$ by employing more labour and energy, or by expanding the number of available varieties through investing to the sector-specific capital stock $J_{i,t}$. The parameter κ measures the substitutability between different varieties $x_{j,i,t}$ (or equivalently, the gains from specialization), and is formally defined as

$\kappa = (\sigma_Q - 1)/\sigma_Q$, where we assume $\sigma_Q > 1$ for the endogenous growth specification. Note that if we set $\kappa = 1$, the model collapses to a standard, Ramsey-type exogenous growth model.

The producer of the intermediate good composite $Q_{i,t}$ maximizes profits on a competitive market, taking all prices as given and solve:

$$\max_{x_{j,i,t}} p^Q_{i,t} Q_{i,t} - \int_{j=0}^{J_{i,t}} p^x_{j,i,t} x_{j,i,t} dj, \text{ w.r.t (A.9)}. \tag{A.10}$$

Where we denote by $p^x_{j,i,t}$ the price of individual intermediate varieties. Solving the optimization problem in equation (A.10) determines the optimal demand for $x_{j,i,t}$:

$$x_{j,i,t} = \left(\frac{p^Q_{i,t}}{p^x_{j,i,t}} \right)^{\frac{1}{1-\kappa}} Q_{i,t}. \tag{A.11}$$

From now on, we assume that all varieties of the sector-specific intermediate good are perfectly symmetrical—each manufacturer of intermediates demands the same amount of labor and energy inputs—so we simplify the notation as $x_{j,i,t} = x_{i,t}$.

Production of intermediate goods

As described in Equation (A.9), what determines the expansion of each production sector i are the amount, variety, and substitutability of different intermediate goods. Moreover, we assume that each intermediate variety $x_{i,t}$ is first invented, and then produced, by a single firm that receives a perpetual patent at the moment of invention. Therefore, the growth rate of the overall economy depends on the decisions of profit-seeking intermediate firms.

i) Capital investments to new varieties

There are two types of capital in the model, as depicted in Figure 1, physical and non-physical, which together make up the sector-specific capital composite $J_{i,t}$. That is, we follow Karydas and Zhang (2019) and Bretschger et al. (2011) and include both a "lab equipment" approach, with I_{P_i} the direct physical investment for sector i, as well as a "scientific labor and R&D" innovation with I_{N_i}, the non-physical investments. The low of motion for the stock of sectoral capital follows:

$$J_{i,t+1} = \left[\alpha_J I_{P_{i,t}}^{\frac{\tau-1}{\tau}} + (1-\alpha_J) I_{N_{i,t}}^{\frac{\varepsilon_J-1}{\varepsilon_J}} \right]^{\frac{\varepsilon_J}{\varepsilon_J-1}} - (1-\delta_t) J_{i,t}, \tag{A.12}$$

with δ_t the depreciation rate of capital. The non-physical investments stems from labor in research $L_{J_{i,t}}$ and investments into R&D, $I_{J_{i,t}}$:

$$I_{N_{i,t}} = \left[\alpha_I L_{J_{i,t}}^{\frac{\omega-1}{\omega}} + (1-\alpha_I) I_{J_{i,t}}^{\frac{\omega-1}{\omega}} \right]^{\frac{\omega}{\omega-1}}, \tag{A.13}$$

The incentives to invest in new varieties stem from the monopoly rent, which is obtained when producing the intermediate goods $x_{i,t}$.

ii) Optimal output of new varieties

In order to produce one unit of output, the intermediate good producers combine two types of inputs, labour $L_{X_{i,t}}$ and energy $E_{i,t}$, according to the following CES technology:

$$x_{i,t} = \left[\lambda_i L_{X_{i,t}}^{\frac{\varepsilon_x-1}{\varepsilon_x}} + (1-\lambda_i) E_{i,t}^{\frac{\varepsilon_x-1}{\varepsilon_x}} \right]^{\frac{\varepsilon_x}{\varepsilon_x-1}}. \tag{A.14}$$

We assume labour $L_{X_{i,t}}$ to be in inelastic supply throughout the modelling horizon, perfectly mobile between sectors within the country. The energy aggregate $E_{i,t}$, on the other hand, is combined from a fossil (F) and fossil-free (G) energy sources, according to:

$$E_{i,t} = \left[\phi_i F_{i,t}^{\frac{\varepsilon_E-1}{\varepsilon_E}} + (1-\phi_i) G_{i,t}^{\frac{\varepsilon_E-1}{\varepsilon_E}} \right]^{\frac{\varepsilon_E}{\varepsilon_E-1}}, \tag{A.15}$$

where the fossil-sources of energy, f_k, oil, gas and heat combine into F under a CES production:

$$F_{i,t} = \left[\sum_k \phi_{i,k} f_{k,i,t}^{\frac{\varepsilon_{fos}-1}{\varepsilon_{fos}}} \right]^{\frac{\varepsilon_{fos}}{\varepsilon_{fos}-1}}, \tag{A.16}$$

the index k denotes each type of fossil energy.

The output decision of the intermediate monopoly is twofold. First, it chooses an optimal bundle of labour and energy inputs as to maximize profits in a perfectly competitive market:

$$\max_{L_{X_{i,t}}, E_{i,t}} = \psi^x_{i,t} x_{i,t} - w_t L_{X_{i,t}} - p^E_{i,t} E_{i,t}, \tag{A.17}$$

where $\psi^x_{i,t}$ is the price that would prevail under a perfectly competitive market. We denote the price of labor w_t and price of energy by $p^E_{k,t}$. Second, the firm exploits its monopoly power in the output market and sets the optimal output price solving:

$$\max_{p^x_{i,t}} = p^x_{i,t} x_{i,t} - \psi^x_{i,t} x_{i,t}, \tag{A.18}$$

taking the demand for $x_{i,t}$ in equation (A.11) as given. Thus, it sets prices according to:

$$p^x_{i,t} = \frac{1}{\kappa} \psi^x_{i,t}, \tag{A.19}$$

with profits being equal to:

$$\pi_{i,t} = (1 - \kappa) p^x_{i,t} x_{i,t}. \tag{A.20}$$

As the individual intermediate goods $x_{i,t}$ are imperfect substitutes, and the intermediate good producer competes in a monopolistic market with an output price $p^x_{i,t}$. The imperfect substituability among $x_{i,t}$ in (A.9) turns into the mark-up $\frac{1}{\kappa} - 1$. The term $1 - \kappa$ in (A.20) measures the share of revenues in the production of Q which is used to compensate firm owners from their investments.

A.3 International trade

The economy is open to trade on the goods' market. In each sector, a domestic and a foreign good are available for consumption and production. We model international trade assuming Armington aggregation, i.e. each sectoral good is an imperfect substitute to an imported sectoral output in consumption. For each sector i, domestic D_i and imported goods M_i are combined according to the following CET function:

$$A_{i,t} = \left[\alpha_A D_{i,t}^{\frac{\xi-1}{\xi}} + (1 - \alpha_A) M_{i,t}^{\frac{\xi-1}{\xi}} \right]^{\frac{\xi}{\xi-1}}, \tag{A.21}$$

where ξ is the elasticity of substitution between the domestic and the foreign good. Note that the domestic good D_i is the share of the final output Y_i that the economy keeps for domestic use. The final goods supplier i at time t maximizes profits taking prices as given according to:

$$\max_{M_{i,t},Y_{i,t}} = p^A_{i,t}A_{i,t} - p^Y_{i,t}D_{i,t} - p^A_{i,t}M_{i,t}, \tag{A.22}$$

subject to (A.21). Trade is balanced in every period and since we model Switzerland as a small open economy, foreign prices are exogenous. The economy exports and imports regular and energy goods and also purchases crude oil and natural gas from abroad. The latter are assembled with the final good Y_i of the oil and gas sector only according to a Leontief production function.

A.4 Equilibrium

The dynamic equilibrium path using the equations derived in this Section A is characterized by a time path of quantities and prices:

$$\{Y_{i,t}, Q_{i,t}, B_{i,t}, x_{i,t}, J_{i,t}, L_{X_{i,t}}, L_{J_{i,t}}, E_{i,t}, A_{i,t}, D_{i,t}, M_{i,t}, I_{P_{i,t}}, I_{N_{i,t}}, \Delta J_{i,t}, C_{Y_{i,t}}, C_{Egyi,t}, C_{i,t}\}_{t=0}^{\infty}$$
$$\{p^Y_{i,t}, p^Q_{i,t}, p^B_{i,t}, p^x_{i,t}, p^J_{i,t}, w_t, p^E_{i,t}, p^A_{i,t}, p^I_{P_{i,t}}, p^I_{N_{i,t}}, p^C_{Y_{i,t}}, p^C_{Egyi,t}, p^C_{i,t}, r_t\}_{t=0}^{\infty}$$

which clear goods and factors markets and satisfy the first order conditions for firms and households.

B Sectoral aggregation

Sector label	Description	NOGA Divisions
AGR	Agriculture	01 - 03
CHM	Chemical Industry	20 - 21
MCH	Machinery and Equipment	26 - 30, 33
EGY	Energy (Electricity, Oil, Gas, Heat)	19, 35, 38
CON	Construction	41 - 43
TRN	Transport	49 - 52
BNK	Banking and Financial Services	64
INS	Insurances	65
HEA	Health	86
OSE	Other Services	36 - 39, 45 - 47, 53 - 63, 68 - 97
OIN	Other Industries	05 - 18, 22 - 25, 31 - 32

Table B.1: Mapping of NOGA divisions to sectors

C Calibration parameters

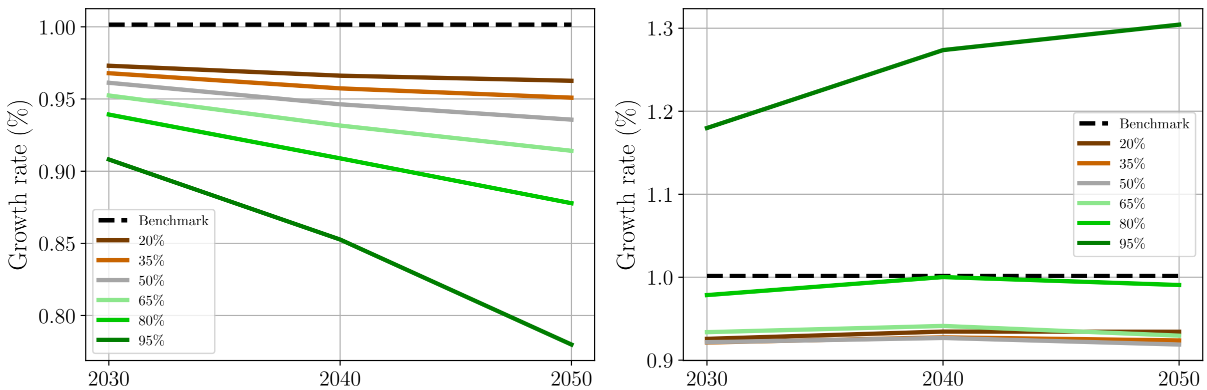
Table C.2: Description and values of the parameters used in the economic model

Model parameters		
Parameter	Description	Value
Elasticities of substitution for production activities		
ε_Y	Intermediate composite Q and inputs B from other sectors	$\star$
ε_x	Labour and energy in intermediate good production	$\star\star$
ε_E	Electricity and non-electricity for intermediate goods production	2.00
ε_{fos}	Types of Fossil energy in intermediate production	1.00
τ	Physical investment I_{P_i} and non-physical investments I_{N_i}	0.30
ω	Labor in research L_{J_i} and investments in R&D I_{J_i}	0.30
κ	Intermediate varieties	0.70
υ	Elasticity of substitution between sectoral outputs for the input B_i	0
Elasticities of substitution for consumption		
σ_C	Energy and non-energy goods in consumption	0.50
σ_E	Energy goods in consumption	2.00
σ_{fos}	Types of Fossil energy in consumption	1.00
σ_Y	Different regular goods	0.50
Elasticities of substitution for welfare		
$1/\zeta$	Intertemporal elasticity of substitution	0.85
σ_L	Consumption and leisure	0.65
Other parameters		
ξ	Trade elasticities	$\star\star\star$
$\bar{r}$	Benchmark Interest rate	0.006
g_K	Benchmark growth rate of capital	0.007
$\bar{\delta}$	Benchmark depreciation rate	0.07
θ	Leisure share in total time endowment of the households	0.40

$\star$: 0.392 (AGR); 0.568 (OIN); 1.264 (CON); 0.848 (Fossil, CHM); 0.518 (MCH); 0.352 (TRN); 0.100 (Electricity); 0.492 (others)
$\star\star$: 0.7 (AGR, MCH, Electricity, Fossil); 0.52 (CON); 0.55 (CHM, TRN, OIN); 0.4 (others)
$\star\star\star$: 3.52 (AGR); 5.06 (MCH); 4.18 (Electricity, OIN); 3.19 (others)

Sources: ε_Y Okagawa and Ban (2008); ε_x Van der Werf (2008), Mohler and Müller (2012); ε_E Papageorgiou et al. (2017); ε_{fos} and σ_{fos} Bretschger and Zhang (2017); τ, ω, ξ Bretschger et al. (2011); σ_C and σ_Y Vöhringer et al. (2007); $1/\zeta$ Hasanov (2007); σ_L Imhof (2012); ξ Donnelly et al. (2004); υ Paltsev et al. (2005)

D Effects of the carbon tax on consumption and investment

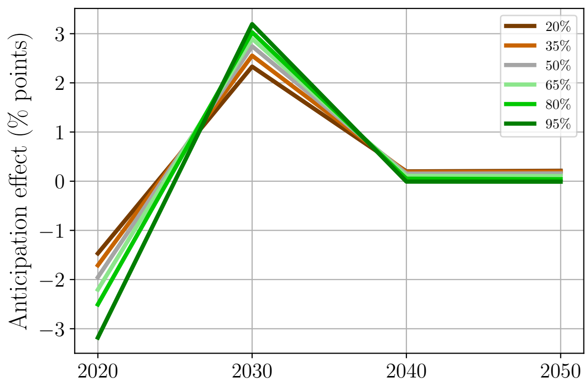


(a) Consumption growth

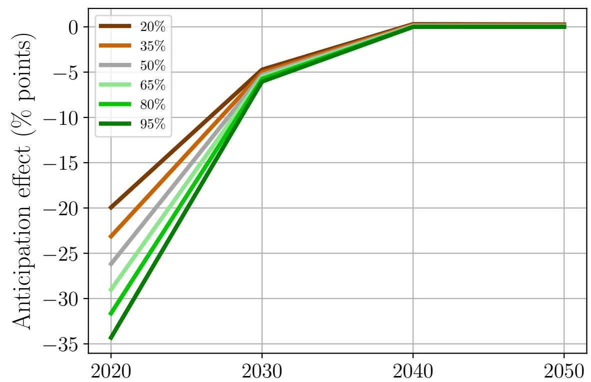
(b) Investments growth

Figure D.1: The effect of carbon reductions on the aggregate consumption growth and investments growth. The figure shows the results for various policy targets under the anticipation of future policies. For example, a 65% policy implies a 65% reduction in CO_2 emissions in comparison to the benchmark year.

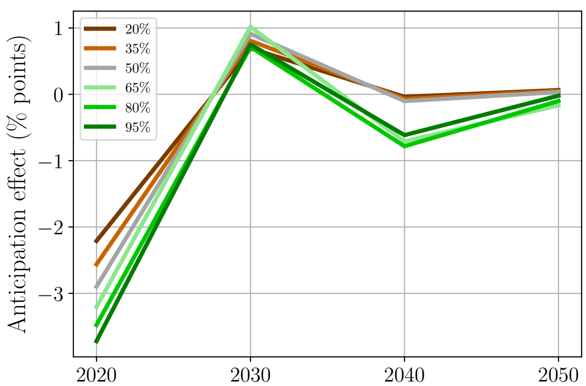
E Anticipation effect on energy use



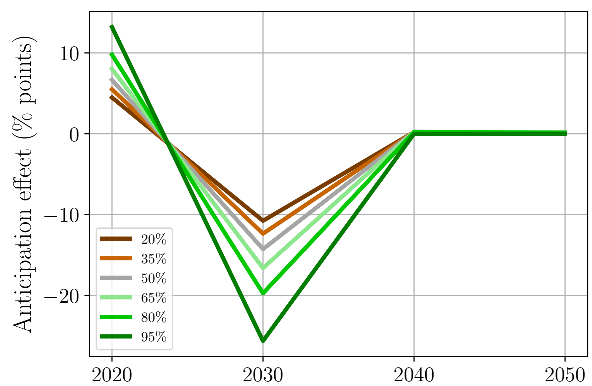
(a) Oil



(b) Gas



(c) Heat



(d) Electricity

Figure E.2: Anticipation effect on the use of energy from different sources.

F Anticipation effect on consumption and leisure

For both graphs, we show the effect of anticipation at various levels of the carbon tax such that the total carbon emissions decrease by 20-95%.

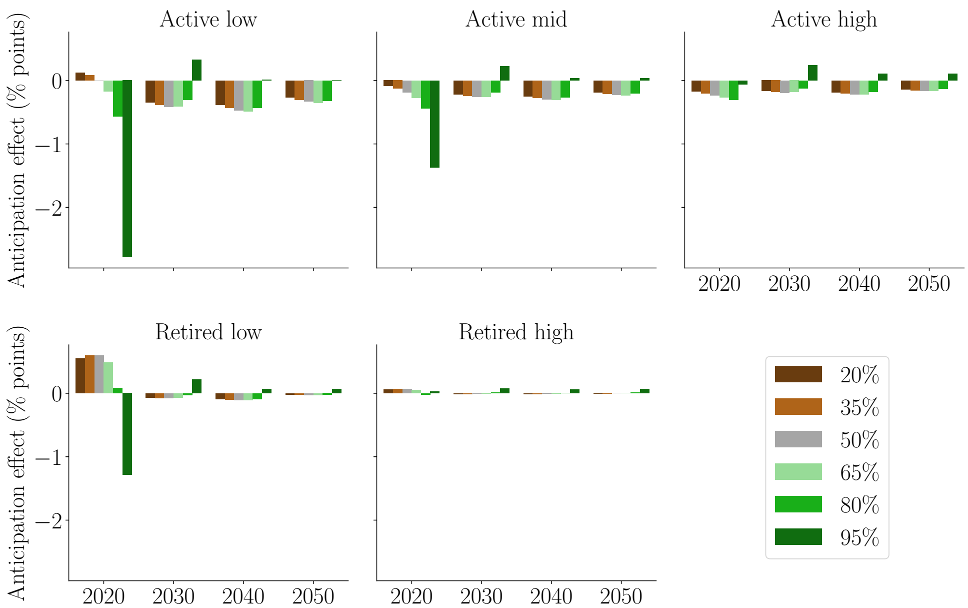


Figure F.3: Anticipation effect on consumption index by household

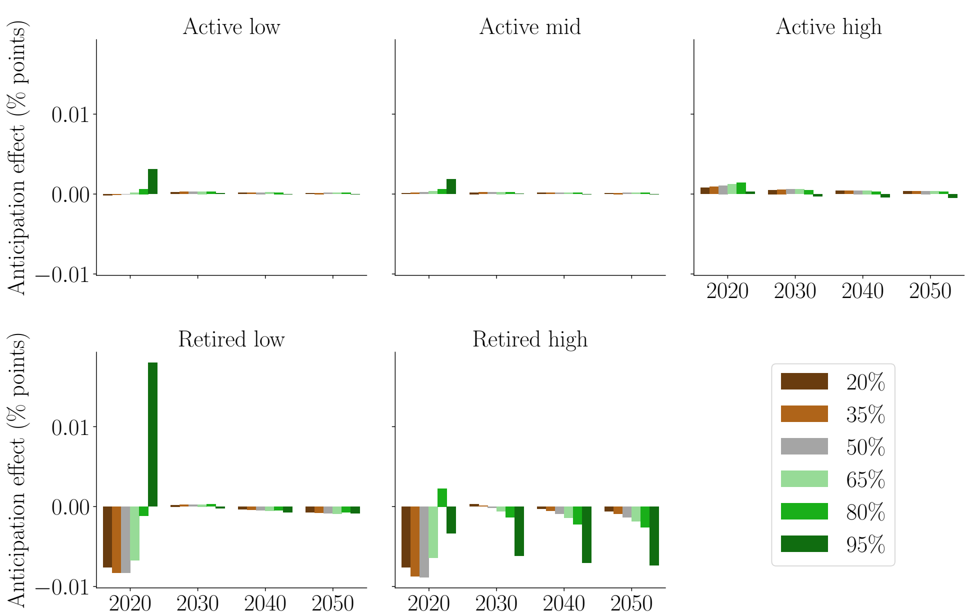


Figure F.4: Anticipation effect on labor supply by household

G Inverse-proportional redistribution

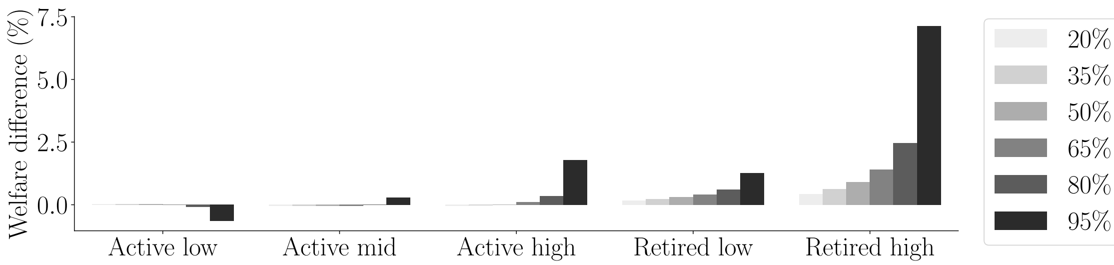


Figure G.5: The difference in welfare between the inverse-proportional and lump-sum redistribution schemes across household groups, the anticipation case. We show the results for scenarios that go from 20% to 95% reduction of carbon emissions. As the graph reads, for a 95% carbon reduction policy, the welfare of the "Retired high" household group increases by about 7.5% when the tax revenues are redistributed inversely proportional to total income compared to the lump-sum redistribution scheme.

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