The Macroeconomics of Climate Change: Starting Points, Tentative Results, and a Way Forward

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Introduction

The purpose of the paper is to outline important starting points for climate-economy modelling, describe some tentative results and draw policy conclusions from them. We end with a discussion of the kinds of research needed going forward.

Within environmental economics, and within economics more generally, the study of climate change is attracting an increasing amount of research. It is increasingly clear that a broad consensus has been built around the notions that (i) emissions of carbon-dioxide and other greenhouse gases drive global warming and (ii) global warming is associated with costs. The first point has been documented by climate scientists in countless research papers and they have been summarized in the IPCC reports. The second point also comprises research by natural scientists but here economists are making important contributions as well. Both on (i) and (ii), there is significant uncertainty; both the understanding of the carbon cycle and the climate system contain many open questions about magnitudes, and the systematic quantification and study of damages from climate change around the world is really just in its infancy. Climate change is a slow process and emissions of carbon dioxide affects the climate for hundreds of years. The consequences of this for the economy and human welfare in general in such a long perspective can never be forecasted with any precision. The fact that these uncertainties are large and unlikely to vanish are central for our policy conclusions. We argue that it is not possible to rule out quite devastating consequences of continuing to emit greenhouse gases at the current rate. Thus, for precautionary reasons it is clear that humankind needs to do something about climate change: we need to limit emissions. If we can establish that a transition to climate neutrality need not be overly costly, it is the obvious way forward. This point of view implies that the key task going forward is to figure out how the transition best can be done. This is more policy relevant than calculating costs of business as usual under debatable or speculative assumptions.

Some observers appear to think that the how question is not so critical and that, rather, we should simply all make a huge effort to stop emissions, to the very best of our abilities. This effort, to the same observers, often tends to take the form of a complete change of lifestyles and, in many cases, a call for growth to stop and, in a few, for a change of economic systems away from markets toward central planning. We find this belief almost as hazardous as climate change denial. To us, the how question is critical precisely because we fear any motto involving "maximal effort": we would rather prescribe a "minimal effort", but of course subject to attaining the same goal. The reason is simple. The less we think about the efficiency of stopping climate change, the more costly we fear that it will be, and the more costly it will be, the higher is the likelihood that the fight to end climate change will be voted down (in democracies; or, in non-democracies, abandoned for lack of party support). Thus, to us, cost efficiency is the crucial subject to study in this area.

To study cost efficiency in combating climate change is one that economists, in principle, should excel at. After all, this is a key part of what we do (and what other scientists clearly do not focus on). We do have the tools and reasonable starting point. As in most other areas of economics, the question at hand is fundamentally quantitative. Thus, it is not sufficient to just state "follow Pigou", especially since carbon taxes are barely implemented anywhere in the world, despite our decades-long recommendations. We thus need to evaluate alternative policies (those that seem politically feasible) and compare them. In this paper, we present examples of such work, but the key is not the work itself but to emphasize some important prerequisites for any such research, namely to use appropriate quantitative inputs in the analysis. Clearly, without them, the analysis will remain abstract, while what policymakers need is concrete suggestions, involving numbers, and a statement to the effect that the suggestions attain the sought-after goals at a comparatively low cost.

We do not attempt a survey of the quantitatively oriented literature but merely assert that much of the research is lacking one of several key quantitative inputs. One is knowledge of the most up-to-date assessments of the nature of the reduced-form link between emissions and warming, e.g., its degree of non-linearity. Another concerns the degrees of uncertainty in various parameters, including those relevant in damage measurements. Furthermore, other important facts include estimates of the stocks (locations, and extraction/refinement costs) of various forms of fossil fuel. We also need to input knowledge about alternative sources of energy services (green technology, nuclear options, etc.). Yet another key input is the degree to which climate policy is already in place in different parts of the world. As an example, we have noted a striking lack of awareness of the climate policy pursued in the EU, including among climate commentators in the EU. These are examples of important facts that serious assessments of climate policy need to confront. We begin this paper by discussing a number of them.

As a second part of our paper, we use a framework for policy analysis that we have developed ourselves, incorporate available quantitative information, and compare some possible policy paths. The third and final part of the paper discusses the most striking weaknesses of our analysis, which we think should be central issues to deal with in the research going forward.

Quantitative starting points

This section covers what we consider key facts to take into account in any discussions of climate policy. We begin by discussing the natural-science part. Here we draw on information from the IPCC and show a convenient summary of it based on Nordhaus's work. This discussion also covers estimates of the remaining amounts of fossil fuel in the ground, in relation to global emissions. We then discuss uncertainty: the remaining aspects of the climate system where we are still far from a complete understanding. After this, we discuss economic damages---interpreted broadly to include all direct and indirect effects on humans---and, finally, summarize the key facts. The discussion of how the economy works is postponed until our next section.

The relation between emissions and the climate

The analysis of the economics of climate change naturally starts with the greenhouse effect, which is the driver of climate change. This effect builds on the fact that electromagnetic radiation in some frequency ranges, particularly in the infrared spectrum, is absorbed by greenhouse gases. This means that energy released in the form of heat radiation from the surface of Earth cannot directly radiate to space. Instead, it has to transit through the atmosphere in less efficient ways until the concentration of greenhouse gases is low enough for the heat to leave in the form of infrared radiation. With more carbon dioxide (CO_2) and other greenhouse gases, the heat must travel to higher altitudes (on average around 6000 meters) before it can leave Earth in the form of radiation. The principle is very similar to that of a blanket put over a person's body. Without the blanket, heat can leave the skin in the form of heat radiation. With the blanket, heat travels in other less efficient ways through the blanket, until it reaches its top where the heat can radiate. A thicker blanket leads to a higher steady-state temperature below it. In the same way, a higher greenhouse gas concentration makes the blanket around Earth thicker, which raises the steady-state temperature below the blanket, i.e., at Earth's ground level.

The greenhouse effect triggers a large number of feedback effects, both in the climate system and in the carbon cycle. These influence the relation between emissions and greenhouse gas concentration. Despite the large complexity of the combination of all these processes, it has recently been shown that an appropriately calibrated version of the 5-equation climate-carbon model set up by Nordhaus for his DICE/RICE models (Nordhaus, 1994) replicates the most advanced Earth System models very well (Folini et al., 2022). It is therefore of value to describe it here.

The 5-equation mapping from emissions to the climate

The climate module in DICE/RICE contains two equations that describe the law of motion for the global mean temperatures in the atmosphere at the Earth's surface, T_t , and in the oceans, T_t^L, both measured as deviations in degrees Celsius from their respective pre-industrial values:

$$T_t - T_{t-1} = \sigma_1 \left(\frac{\eta}{\ln 2} \ln\left(\frac{S_{t-1}}{S_0}\right) - \kappa T_{t-1} - \sigma_2 (T_{t-1} - T_{t-1}^L) \right) \tag{1}$$

$$T_t^L - T_{t-1}^L = \sigma_3 (T_{t-1} - T_{t-1}^L) \quad . \tag{2}$$

The right-hand side of the first equation contains an expression consisting of three terms within bracket: $\frac{\eta}{\ln 2} \ln\left(\frac{S_{t-1}}{S_0}\right)$, $-\kappa T_{t-1}$ and $-\sigma_2 (T_{t-1} - T_{t-1}^L)$ These terms represent the key changes in energy fluxes (flows per unit of area) to and from the atmosphere that drive climate change. The changes use their pre-industrial levels as baseline and are measured in *W/m²*. Their sum is called the atmospheric energy balance. If the balance is positive, heat is accumulated, i.e., the atmospheric temperature increases. The change in temperature per period is proportional to the surplus in the energy budget with a proportionality coefficient σ_1.

The first term within brackets in (1) captures the greenhouse effect and contains the ratio $\frac{S_{t-1}}{S_0}$ where S_{t-1}represents the amount of carbon dioxide in the atmosphere in period *t*-1 and $S_0$is the pre-industrial amount. This first term is called CO_2 forcing in the literature. It is known since long (Arrhenius, 1896) that a good approximation to the strength of CO_2 forcing is that it is proportional to the logarithm of the ratio of the current concentration and its pre-industrial value. The parameter η is 3.45, implying that a doubling of the CO_2 concentration leads to an increase in the energy budget of 3.45 W/m² ceteris paribus.[4]

[4] To obtain an understanding of orders of magnitude, note that the area of Earth is around 500 million km². A doubling of the CO_2 concentration thus adds 1.725*10^{15} W to Earth's energy budget. This is close to the power of two million nuclear power plants (we have currently around 440 in operation).

The second term in (1) captures the fact that as Earth is warmed up, more energy is radiated out into space. The effect is approximated to be linear in T_t_with a proportionality constant κ =1.06. The third term in (1) represents the cooling effect that arises if the ocean is cooler than the atmosphere. This term is also approximated to be linear in the temperature difference $(T_{t-1} - T_{t-1}^L)$. Finally, equation (2) describes the dynamics of the ocean temperature. The only mechanism that changes the ocean temperature is the flow of heat between the atmosphere and the ocean, which as noted is proportional to $(T_{t-1} - T_{t-1}^L)$. Here it enters as in (1), but with the opposite sign. Since the heat capacity of the oceans is much larger than that of the atmosphere, $\sigma_1 >> \sigma_3$.

It is immediate that the system (1)-(2)) is stable. It is also clear that a doubling of the CO_2 concentration implies a steady state where$T = T^L = \frac{\eta}{\kappa}$. This ratio is called the *Equilibrium Climate Sensitivity* (ECS).[5] The latest IPPC report states a best guess of 3°C per doubling of the CO_2 concentration.

The second module in the model is a description of the carbon cycle, or carbon circulation. This is a simple system of three linear difference equations, each describing the change in the size of three reservoirs of carbon (often called carbon sinks). The first, S_t -- the atmosphere -- is already mentioned and measured in GtC (billion tons of carbon).[6] The other two reservoirs are denoted S_t^U and S_t^L and are also measured in GtC. It is necessary to have these two additional reservoirs in the model because the carbon-cycle dynamics are driven by both a relatively rapid flow between the atmosphere, the biosphere, and the surface ocean and a much slower one involving the deep oceans. The dynamics of the reservoirs are given by a linear system where flows are proportional to source reservoirs and emissions are denoted by *E*:

$$S_t - S_{t-1} = -\phi_{12} S_{t-1} + \phi_{21} S_{t-1}^U + E_{t-1} \qquad (3)$$

$$S_t^U - S_{t-1}^U = \phi_{12} S_{t-1} - (\phi_{21} + \phi_{23}) S_{t-1}^U + \phi_{32} S_{t-1}^L \qquad (4)$$

$$S_t^L - S_{t-1}^L = \phi_{23} S_{t-1}^U - \phi_{32} S_{t-1}^L \qquad (5)$$

Equations (1) -- (5) describe the relation between emissions E_t and climate change, as represented by the global mean atmospheric temperature at ground level.[7,8]

As noted, this compact system shows a surprisingly good accordance with the most advanced Earth System Models (Folini et al., 2022). Based on the IPCC, Golosov et al. (2014) discuss a summary description of the carbon cycle that remains valid. This summary describes the carbon cycle as having

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[5] Note that natural scientists use the word "equilibrium" to mean what economists call "steady state".

[6] A ton of carbon C produces 3.67tons of carbon dioxide CO_2 when combusted.

[7] The parameters are $\sigma_1 = 0.137, \sigma_2 = 0.73, \sigma_3 = 0.00689, \eta = 3.45, \kappa = 1.06,$, ϕ_{12}=0.053, ϕ_{21}=0.0536, ϕ_{23}=0.0042, and ϕ_{32}=0.001422 for a time step of one year. The initial values are $T_{2015} = 1.078, T_{2015}^L = 0.3132, S_{2015} = 850, S_{2015}^U = 765$ and $S_{2015}^U = 1799.$

[8] Other features, in particular the emission of aerosols and methane, are important for the climate but omitted here. Their impacts are quite substantial but much more short-lived than that of CO_2.

three important characteristics: (i) about half of the emitted CO_2 leaves the atmosphere within a few decades; (ii) between one fifth and a quarter stays for thousands of years; and (iii) the remainder leaves the atmosphere with a half-life of a few hundred years.

CO_2 is the most important greenhouse gas in terms of human influence on Earth's energy balance. The second is methane. The dynamics of the methane concentration is simpler since the decay is approximately geometric with a half-life of 9 years. Since methane leaves the atmosphere so relatively fast, it is large the flow of methane emissions that affect the energy balance. To incorporate the effect of methane in the model, an additive methane forcing

We summarize the description so far as follows.

Observation 1. *A simple 5-equation difference equation describes the relation between emissions of CO_2 and global warming quite well qualitatively as well as quantitatively.*

Emissions and stocks of fossil fuel

Current global emissions of CO_2 are approximately 35 $GtCO_2$ per year, i.e., around 10GtC/year. Over the last 50 years at least, the growth rate of emissions has been lower than the growth rate of GDP. Over the last 20 years the growth rate of emissions has fallen substantially but not to negative rates, apart from the temporary effects of the pandemic (see Figure 1.) In the EU and the U.S., on the other hand, emissions have fallen over the last two decades. It is sometimes conjectured that this is due to carbon leakage, i.e., that carbon-intensive production has moved to countries with more lax climate policies, in particular to China and India. A way to analyze this is to compare production- and consumption-based emissions. The former are the standard territorial emissions. The latter are emissions associated with the production of the consumption and investment goods used in a country, regardless of where the production took place. If the fall in production-based emissions is due to carbon leakage, it would be visible as different trends in the two measures.

The bottom left panel of Figure 1 shows production- and consumption-based emissions for the EU and the U.S. and we see that although the consumption-based measures started falling a few years later than the production-based measure, the trends of the two series are very similar during the last two decades. The other side of the coin is that in China and India, whose emissions have increased dramatically, also have parallel trends for the two emission measures.

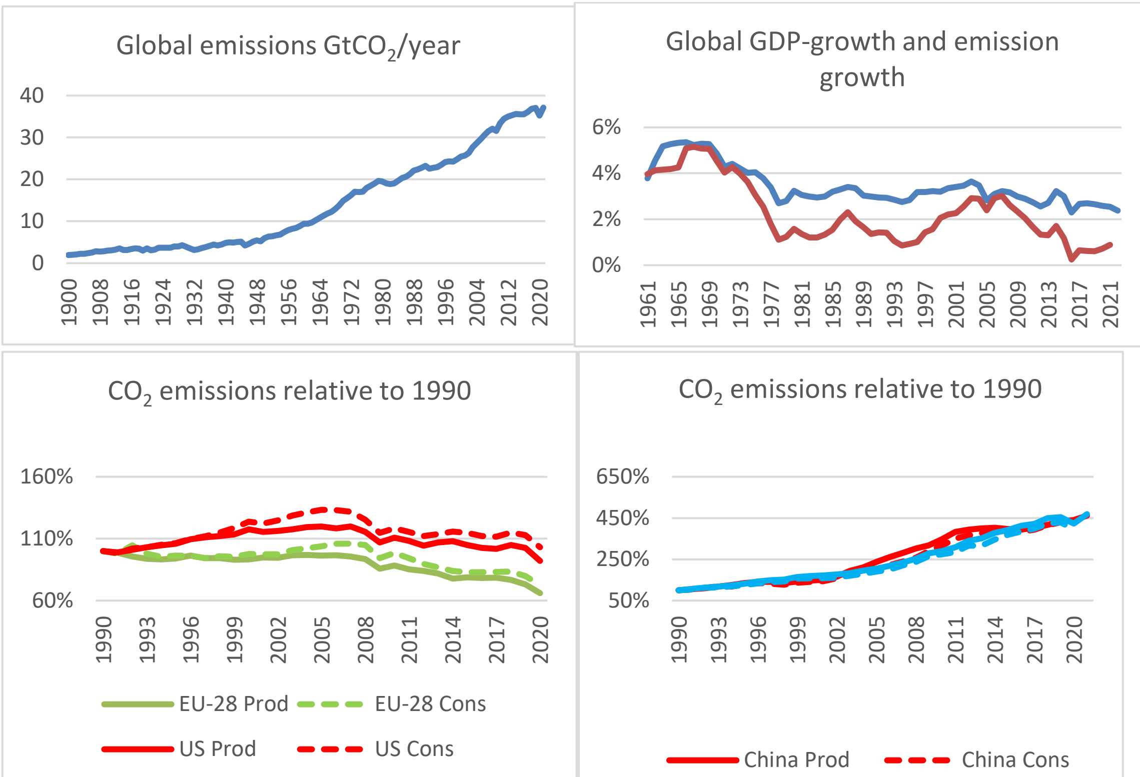

Figure 1. Various measures of CO_2 emissions. Data sources: Our World in Data 2023 and World Bank National Accounts.

Observation 2. *Global CO_2 emissions are not falling, but increase at a lower rate than two decades ago. Both consumption- and production-based emissions have fallen in the EU and the U.S. over the same period, whereas the opposite is true for emissions in China and India.*

How much fossil fuel still in the ground is uncertain and depends on how it is classified. A common classification is "proven reserves", which is interpreted as known reserves that are profitable to recover with current technologies and prices. Obviously, prices as well as technology change, and with them the amount of proven reserves. "Recoverable resources" is a wider concept that does not require extraction to be currently profitable. There are many different data sources and the estimates differ across them. IEA (2022) provides estimates for proven reserves and resources. For oil, they are 202 and 715 GtC, respectively; for natural gas, proven reserves and resources are 112 and 412 GtC, respectively; and for coal, reserves and resources are 753 and 14 562 GtC, respectively.[9]

Of the proven reserves of oil and natural gas, some are very cheap to extract. This the case for much or most of the oil in the Middle East oil, which is 51% of the total reserves. How much is uncertain, but as a benchmark in our calculations, we will assume that the amount of fossil fuel with extraction costs that

[9] Oil is measured in barrels, natural gas in m³ and coal in tons. To convert to GtC, we used the following conversion factors; 7.33 barrels of oil per ton, carbon content of oil 84.6%, natural gas 0.511 kgC/m³ and the carbon content of coal is set to 70%.

are negligible relative to the market price is 140 GtC, corresponding to 500GtCO_2.This is approximately half of the proven reserves for oil and natural gas.

Using the 5-equation model

Let us now use the five-equation model to describe three hypothetical scenarios of which two leads to climate neutrality. The first scenario is that emissions simply continue at the current rate of 10 GtC/year; the second scenario is that they continue at 10 GtC/year until 2050 and then fall to zero; and the third scenario is that emissions are phased out linearly from 2025 to reach zero at 2050. The results are depicted in Figure 2.

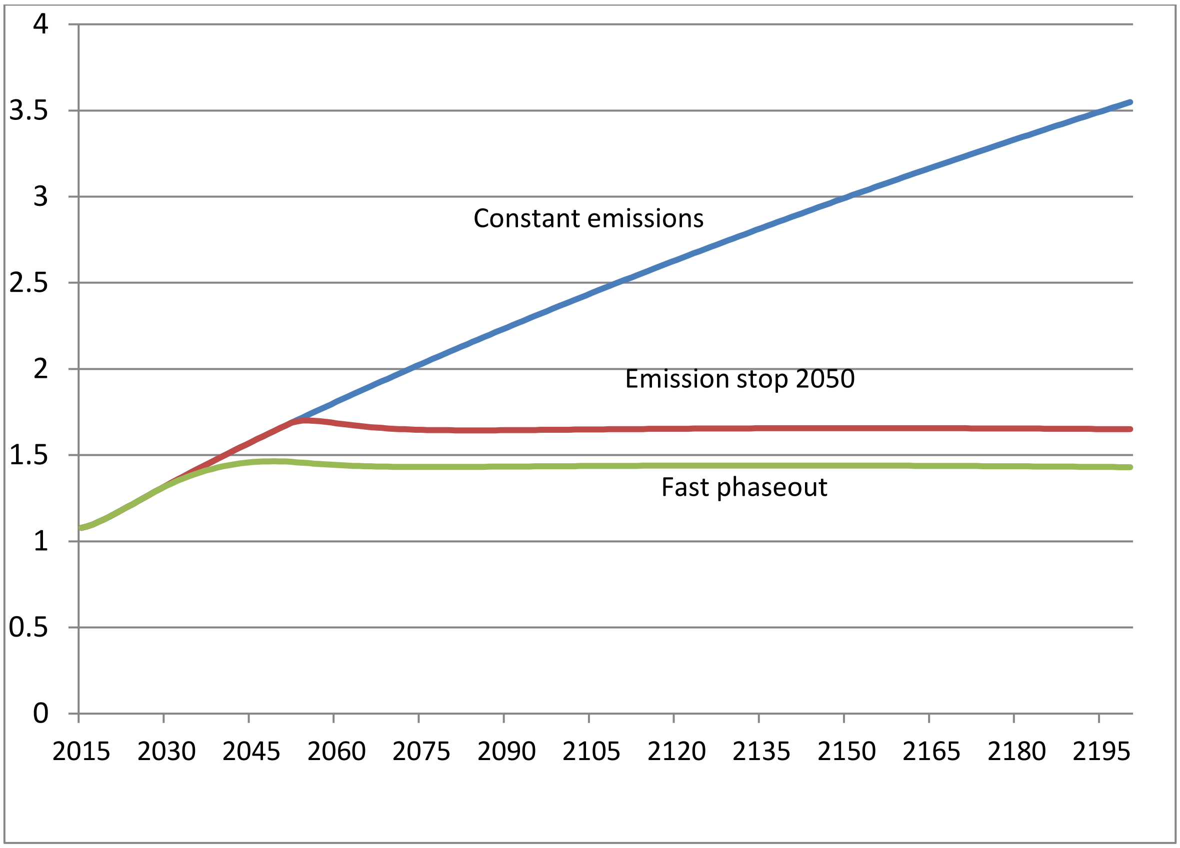

Figure 2. Simulated global mean temperature for three emission scenarios.

Two important results stand out from the simulation. First, if emissions continue at a constant rate, the temperature increases steadily, as an almost linear function of time. Second, when emissions stop, the temperature stays almost constant thereafter. The key insight can be summarized as follows.

Observation 3. *Global warming is approximately proportional to the cumulative emissions of CO_2, both in the short and in the long run.*

In the climate literature, this is now a well-established result, which carries several messages. One is that CO_2 emissions can be treated as permanent: since it is the cumulative emissions, i.e., not accounting for any form of "depreciation", that matter, a given emission unit raises the temperature at once and forever (by a fixed amount). A second message is that in order to hit a certain temperature target at a given point in the future, the timing of the emissions up to that point does not matter; only the sum over the period matters. This insight is also the basis for the calculation of carbon budgets that quantify how much more CO_2 emissions can be accepted without breaching a given temperature ceiling.

IPCC (2021) calculates the remaining carbon from the start of 2020. For a 50% chance of staying below 1.5 and 2°C global warming, they are 500 and 1350 $GtCO_2$. This corresponds to 137 and 369 GtC. This should be compared to the estimates of reserves and resources of fossil fuel still left to extract.

Observation 4. *The amount fossil fuel left in ground is very large compared to the carbon budgets for 1.5 and 2°C global warming. The amount of oil and gas with low extraction cost is in the same order of magnitude as these carbon budgets.*

Third, it is important to note that the linearity result runs counter to the popular belief that the global climate system is close to a tipping point where the relation between emissions and climate change abruptly and perhaps irreversibly change. In the sixth IPCC report on the Physical Science Basis, it is stated ""there is no evidence of such non-linear responses at the global scale in climate projections for the next century, which indicate a near-linear dependence of global temperature on cumulative GHG emissions."(IPCC, 2021, page 202). This feature is depicted in Figure 3 from IPCC, which shows the relation between accumulated emissions and the global mean temperature using both historic data up to the current amount of emissions of around 650 GtC and simulations of future scenarios from different Earth System models.[10] As we can see, different simulations provide different slope coefficients but they share the linearity qualitatively. We will return below to this uncertainty, which will be key for the policy conclusions. It is also important to note that we are discussing the global mean temperature. It is well known that regional tipping points are likely.

[10] One GtC equals one PgC and corresponds to 3.67 $GtCO_2$.

Figure 3. Relation between cumulative CO_2 emissions and climate change. Source: Figure TS.18 in IPCC, 2021: Technical Summary.

The result from Observation 3, that the temperature stays constant after the accumulation of emissions ends can be understood by examining the three terms of (1). First, since σ_1 is relatively large, the atmospheric temperature T_t changes relatively fast to reach a constant level for given values of the slow-moving variables S_t and T_t^L. Second, for the temperature to stay constant, the sum of the terms must be zero and remain zero. That the temperature remains constant implies that the second term, i.e., the outflow of energy to space $(-\kappa T_{t-1})$ is constant. However, the first term, i.e., CO_2-forcing $\left(\frac{\eta}{\ln 2}\ln\left(\frac{S_{t-1}}{S_0}\right)\right)$ is not constant. It is slowly falling due to the slow removal of CO_2 from the atmosphere. The third term, the cooling effect due to oceans not having heated as much as the atmosphere $\left(-\sigma_2(T_{t-1} - T_{t-1}^L)\right)$ is also falling in absolute value since the oceans are slowly heating up. Since σ_3 is low, this is a slow process. Simply by accident, however, it turns out that the two terms fall in absolute value at about the same rate, implying that their sum, and thus temperature, is constant. To use the analogy with greenhouse gases being a blanket. We can think of lying in a bed with a blanket and a mattress that initially is cold. Over time, the blanket becomes thinner but the mattress is heated by your body so that the temperature remains constant. This finding is relatively recent (Allen et al., 2009) but has gained broad recognition.

The discussion so far describes the evolution of the global mean temperature. It is, of course, not only this measure that affects our economies and human welfare in general. Much attention is given to extreme weather events. It is almost self-evident that at least some types of extreme events, like heat waves, must become more frequent and intense. Since warmer air can hold more humidity, it is also clear that precipitation increases, including its extremes. Figure 4 shows the relation between the global mean temperature and the frequency and intensity of extreme weather events. Also here we see a linear relation. As we keep accumulating CO_2 emissions, the frequency and intensity of extreme weather events increase linearly. In panels (a)--(c), the uncertainty ranges are indicated by triangles. We see that the uncertainty is large also here. Taking this into account, we arrive at another summary observation.

Observation 5. *The frequency and intensity of weather extremes are likely (but not surely) linear in the global mean temperature.*

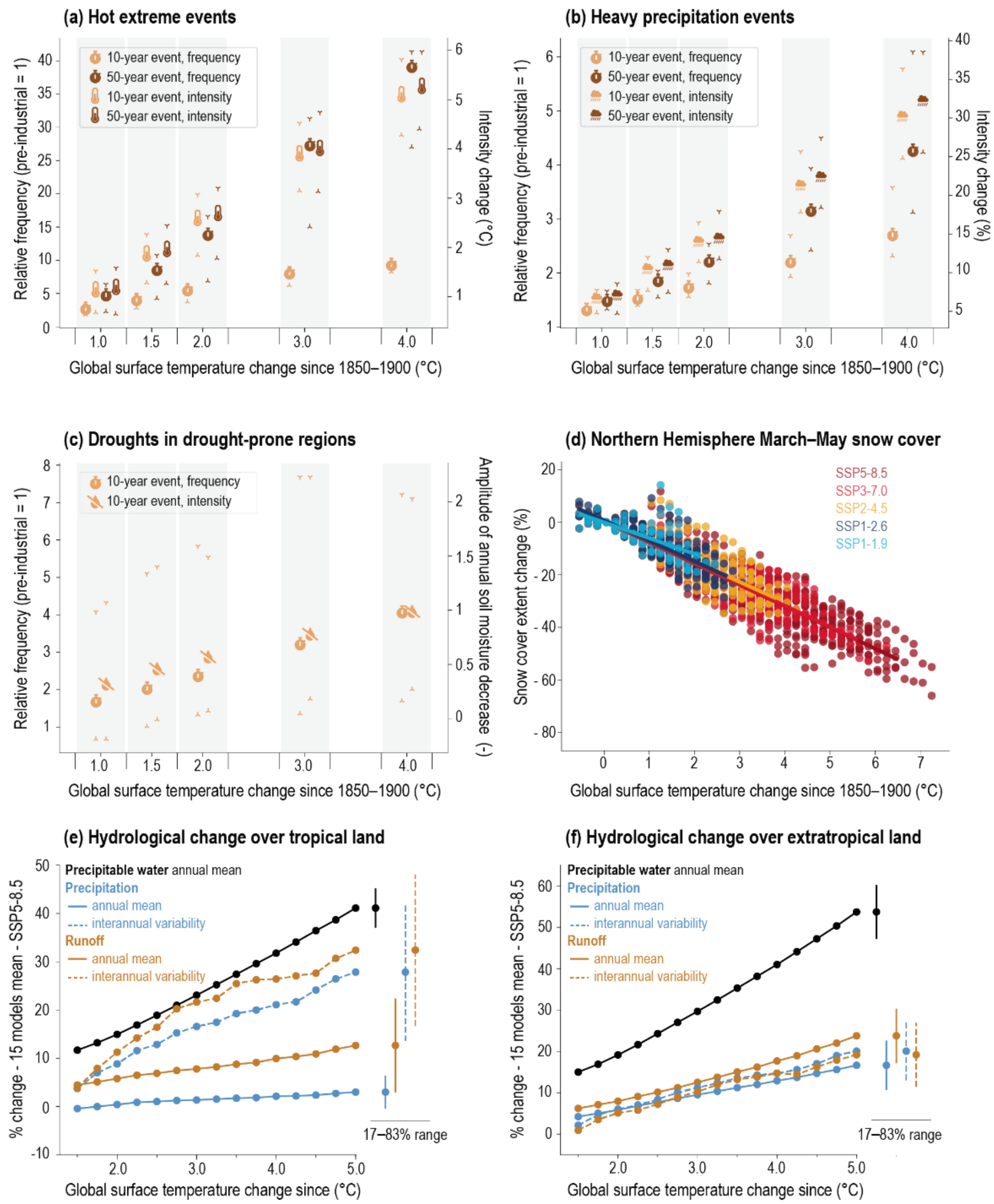

Figure 4. Relation between the global mean temperature, extreme weather events and precipitation. Source: Figure TS.12 in IPCC, 2021: Technical Summary.

Uncertainty

The linearity result discussed above is obviously quite useful for modeling and for policy analysis. However, the usefulness is reduced by the large uncertainty around the point estimates of the proportionality coefficients. The IPPC (IPCC, 2021) specifies a likely uncertainty interval of 1.0 to 2.3°C/TtC with a best estimate of 1.65.[11] The most important source of uncertainty is associated with the equilibrium climate sensitivity (global warming per doubling of the CO_2 concentration), and in particular

[11] This corresponds to 0.27--0.63°C/TtCO_2 with a best estimate of 0.45.

with the parameter κ that quantifies the relation between global warming and the outflow of energy to space. The IPCC provides a likely confidence interval for the equilibrium climate sensitivity of 2.5 to 4°C and a very likely interval of 2 to 5. It states that one should interpret likely as implying a 2/3 probability and very likely as a 90% probability. There is also a substantial amount of uncertainty around how much warming humans have already caused. The IPCC states it to be between 0.8 and 1.3°C.[12]

To gauge the range of the uncertainty, we can note that the accumulated amount of emissions since 1850 is estimated to be 650 GtC. Emitting the same amount once more (which would take around 65 years with the current global emission rate) would likely lead to additional global warming between 0.65 and 1.5°C. Adding this to an uncertain starting point clearly produces large uncertainty regarding where we are going. These simple examples are using the likely uncertainty intervals. As we have seen, the IPCC cannot rule out either much higher or much lower climate sensitivities. Furthermore, also the linearity result is uncertain beyond the current century, in particular if the temperature increases more than two degrees Celsius. It is also important to note that the confidence intervals, although expressed in probability terms, are not based on formal probabilistic analysis but rather on a judgmental assessment of many sources of information including both simulations and historical relations. It is clear that it is not possible to provide an objective probability for unlikely possibilities, such as for climate sensitivity to exceed 5°C. The uncertainty around such possibilities is thus fundamentally Knightian.

The large uncertainty around the relation between emissions and global warming has been somewhat reduced as a result of climate research. For example, the likely range for the equilibrium climate sensitivity was said to be 1.5 to 4.5°C in the fifth IPPC report, which is wider at both ends than the range in the sixth report. Over a longer perspective, however, it is not clear that we are on a trend where uncertainty is falling. How the estimates have changed over the 6 assessment reports from the IPCC is

[12] A key source of uncertainty is the extent of the cooling effect of atmospheric aerosols caused by humans.

shown in Figure 5.

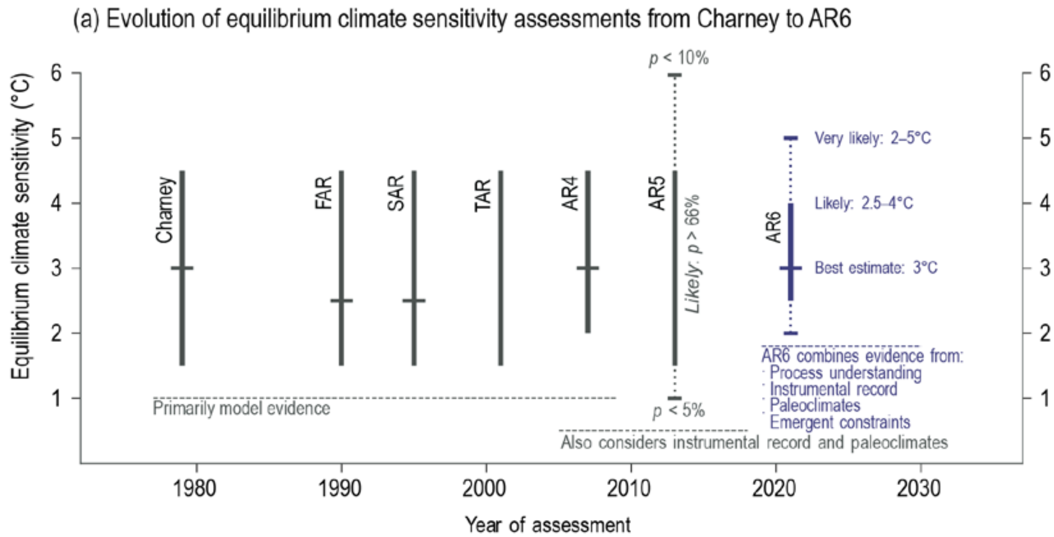

Figure 5. The assessed uncertainty of the equilibrium climate sensitivity across the IPCC reports. Source: Figure TS.16 in IPCC, 2021: Technical Summary.

Observation 6. *The uncertainty around the relation between emissions and climate changes is large, essentially Knigthian and does not appear to be vanishing.*

The relation between global warming and welfare

There is now a fairly large and quickly expanding literature on the consequences for the economy of climate change. Most of this literature deals with particular mechanisms in particular regions. For climate policy, however, it is necessary to aggregate these effects over all relevant mechanisms as well as over time and across space. It is obvious that such an aggregation is a formidable endeavor. Relatively few aggregate studies are undertaken and two meta-studies are available: Nordhaus and Moffat (2017) and Howard and Sterner (2017). The results, of the latter study including the authors best aggregation is shown in Figure 6. Clearly, different specific studies have come to very different results.

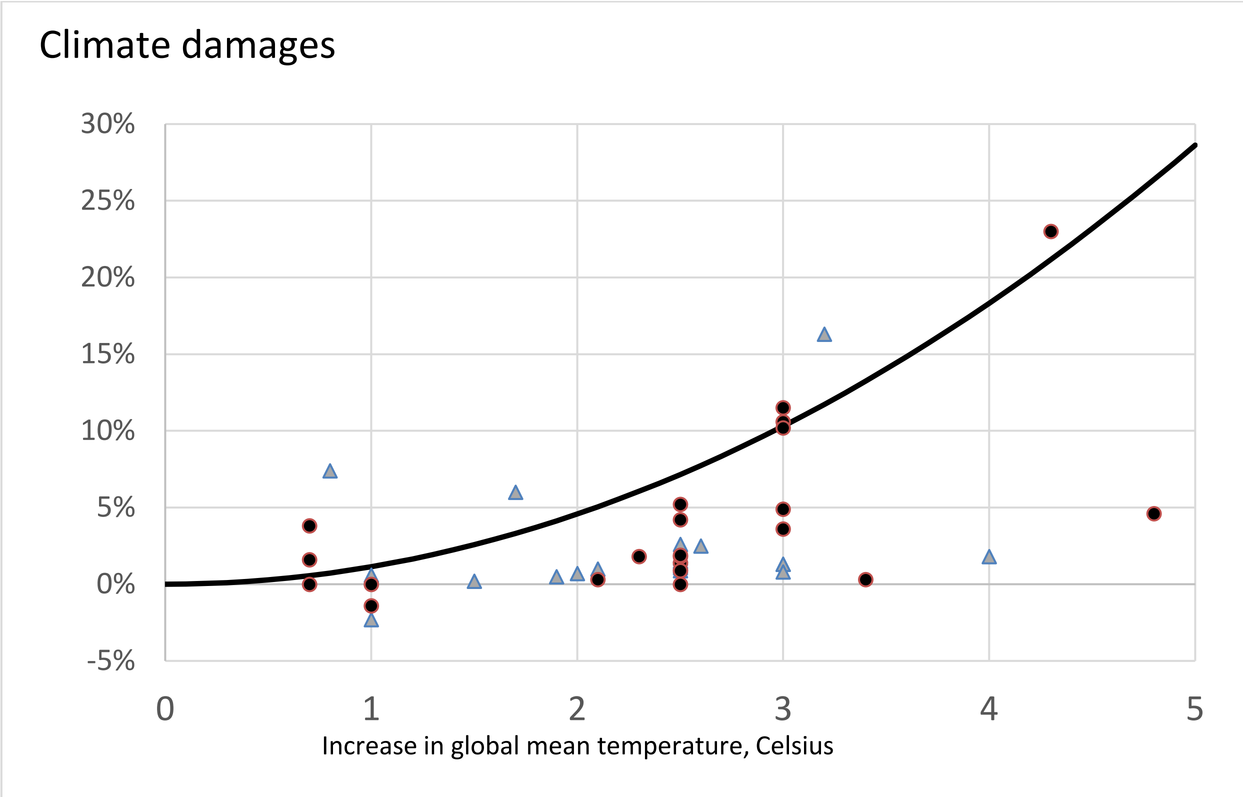

Figure 6. Meta-study of climate damages. Triangles are variations of previous studies that are given less weight in the aggregate relationship depicted by the solid line. Data source: Howard and Sterner, (2017)

Studies on the aggregate relation between climate change and the economy can be organized into two quite different groups: reduced-form and bottom-up approaches. The former are straightforward applications where aggregate variables like GDP or mortality are projected onto observed weather, or weather averages over intervals of time. Although we think of changes in the climate as a more or less permanent change in the distribution of weather events, also shorter, natural weather variations might have effects that are similar to those of permanent changes. If, for example, a decade or a year is warmer than the long-run average temperature, it could have effects that provide information about the effect of a permanently warmer climate. There are two advantages of the reduced-form approach. First, it directly aggregates over all potential mechanisms behind the relation from climate change to outcomes. Second, although human activity drives climate change, variations in temperature at, say the country level, on shorter time scales can be considered exogenous to economic activity. A prototype regression is of the form used in Burke et al. (2015), a study much used in the literature and by organizations like IMF:

$$\Delta y_{i,t} = \beta_1 T_{i,t} + \beta_2 T_{i,t}^2 + \mu_i + \nu_t + \gamma_{1,i} t + \gamma_{2,i} t^2 + \varepsilon_{i,t}$$

where $\Delta y_{i,t}$ and $T_{i,t}$ is the GDP growth rate and temperature, respectively, in country *i* in period *t*. Country and time fixed effects as well as country-specific linear-quadratic time trends are included. This and similar studies typically find a positive β_1 and a negative β_2, implying a positive effect on growth from warming if the national temperature is sufficiently low and a negative effect otherwise. The bliss point is estimated to be around 11°C.

By aggregating over countries, a global aggregate climate damage function can be constructed. Burke et al. provide such an aggregation, which is approximately in line with the preferred meta-study aggregation in Howard and Sterner (2017). The problem with the Burke et al. (2015) study, however, is that its implications on the national levels are hard to take seriously. We examined the effects of the estimates of β_1 and β_2 on national outcomes. For this, we fed in the projections of the changes in national temperatures in EU-15 under a path that leads to global warming of 2.5 degrees by the end of the century; this temperature scenario is similar to what is expected under the current commitments to climate policy in the world. Within EU-15, then, climate change would lead to an enormous GDP divergence of GDP. Sweden would gain more than 500% of GDP from climate change and Finland even more, while Portugal would lose 32%, as seen in Figure 7. That these effects would materialize is hard to believe. Moreover, these extreme effects of average temperature on GDP are hard to square with the relationship between temperature and output within Europe today: it would take enormous, counteracting endogenous effects to explain the rather small differences in output across European countries today given the rather large differences in countries' average temperatures.

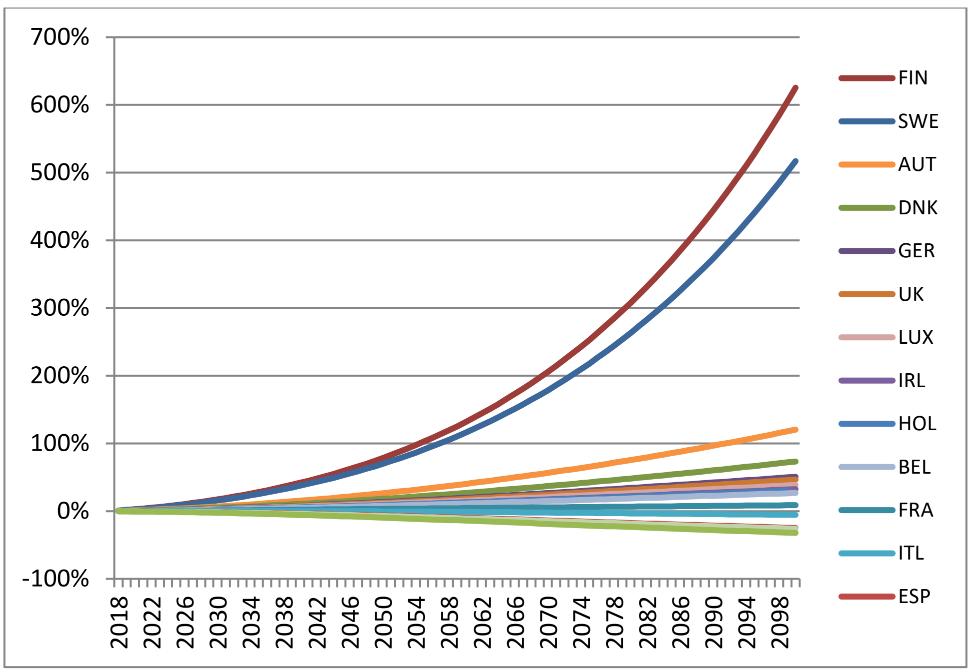

Figure 7. Effects on GDP from a gradual increase in the global mean temperature to 2.5°C above the preindustrial level by the end of the century. Source: Own calculations based on estimates in Burke et al., (2015).

The other type of studies, using the bottom-up approach, first specify a set of mechanisms through which climate change can affect the economy. Then for each mechanism and geographical region, a relation between climate change and the studied effect is quantified. For some mechanisms, structural quantitative models can be used, for example for agriculture. A prototype for these kinds of studies is the original study Nordhaus, (1994). Few similar studies have been produced since Nordhaus's work. A recent and much more detailed study is the Peseta IV report. This quantifies the effects of climate change through river floods, coastal floods, effects on agriculture, other effects from droughts, windstorms, energy supply, and human mortality. The authors use a high-resolution description of these effects but only study the EU and the UK. The baseline is a scenario where climate change is affecting the current economy instantaneously so that no adaptation is possible. The study also considers adaptation and shows that a large share of the effects can be removed by proper adaptation, such as by building seawalls. Figure 8 shows the effects in five regions of the EU as well as for the aggregate.

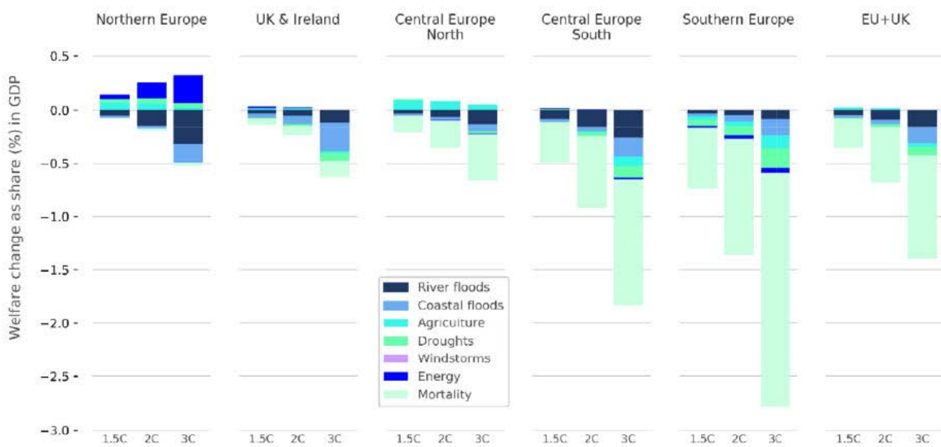

Figure 8 Pre-adaptation climate damages in EU. Source: EU Commission, (2020), Peseta IV report.

The effects in Figure 8 are small overall. They are somewhat higher in the southern parts of the EU; there, damages are dominated by increased mortality in association with heatwaves. Such damages are likely to be possible to adapt to by installing air condition, in particular within elderly care.

Studies like the Peseta study in our view provide credible information about the consequences of climate change. The key problem is that the list of mechanisms very likely excludes important channels. The Peseta study acknowledges this weakness quite clearly and mentions that potentially important impacts, for example on the displacement of people, conflicts and security, and biodiversity are not quantified, and certainly this list of omissions is also far from exhaustive.

The Peseta study points to mortality as a key mechanism whereby climate change affects welfare. Carleton et al., (2022) recently provided a global study on the mortality effects of climate change. They also provide estimates of costly adaptation based on a revealed preference methodology. They can thus also infer how economic growth can increase the ability and willingness to cope with a warmer climate. In an extreme emission scenario where the best guess of the increase in the global mean temperature is around 5°C by the end of this century, they estimate the global cost due to increased mortality to 3.2% of GDP. This includes both higher mortality and costly adaptation. A striking result of the analysis is the large uncertainty. They provide a 50% confidence interval which is minus 5.4 to plus 9.1 % of GDP.

Equally striking is the large variation across different parts of the world. For Europe and the U.S., the estimates are 0.1% and 1.0% while for Bangladesh and Pakistan, they are 18.5 and 27.5%

We conclude this section by the following summary.

Observation 7. *Credible bottom-up quantifications of the effects of climate change point to fairly small aggregate impacts in the advanced economies. These studies suffer from not being able to ascertain that the list of covered mechanisms is exhaustive. Reduced-form time series approaches can be informative but extrapolations are unconvincing. Estimates of increased mortality are highly uncertain and heterogenous.*

Taking stock

Climate science has made impressive advancements in our understanding of the consequences of emitting CO_2 and other greenhouse gases. The implications of these emissions are extremely heterogeneous but all directly related to the change in the global mean temperature which, according to our best understanding, is approximately linear in global cumulative CO_2 emissions, at least for the coming 100 years. The linearity implies a smooth increase in the climate that continues as long as we keep emitting carbon dioxide. However, there is a large degree of uncertainty around the strength in this linear relation. Nonlinearities, including global tipping points, cannot be ruled out, in particular in the long run. Risks for non-linear relations at a regional scale and for the probability and intensity of extreme weather events are larger and more acute.

Our understanding of the quantitative consequences of climate change for human welfare is more limited. Existing studies point to relatively small aggregate impacts, in particular in the advanced economies. However, many of the effects considered are extremely hard to convincingly predict. Current climate policies around the world together suggest global warming that, towards the end of the century, makes it physiologically impossible to work outdoors during the recurring heatwaves in densely populated areas of India. The impact of these events depends on how rich and technologically advanced India will be at that point in time, something which is hard to predict. In addition, many of the most worrisome consequences of climate change are hardly observable yet in the data. Reduced-form econometric studies therefore can only give us limited information. The consequences of exceeding unlikely, but possible, tipping points in the global climate, are even harder to assess. Attempts to quantify the aggregate impacts of climate change are therefore highly uncertain and the uncertainty is Knigthian. In our view, this limits the value of cost-benefit analysis aimed at determining an appropriate overall emission path, or at narrowing down a range for "the" social cost of carbon.

In a situation with high uncertainty, the value of waiting to make decisions is often high. However, the high value of waiting stems from an associated high flow of information. In the case of climate change, the uncertainty is not on a clear downward sloping path: neither the climate-science uncertainty nor the uncertainty about damages seem to be shrinking appreciably as time goes by. Furthermore, waiting implies accumulating more CO_2 emissions, which year by year increases global warming and potentially damaging consequences. Thus, the value of waiting is low while the cost of waiting is high. Thus, the "wait and see" strategy can thus be dismissed.

Given the large amount of Knigthian uncertainty and a net cost of waiting, our view is that a robust climate policy should be sought for. A robust policy is one that provides acceptable outcomes for a large set of realizations of the variables we are uncertain about. It is thus a low regret policy. For us, this cannot mean anything but a significant reduction in the global emission of greenhouse gases, with the aim of reaching zero well before the end of the century. To this end, economic models can be highly useful, not so much for optimizing the degree and timing of abatement but for studying by how---through which kinds of policy interventions---a given amount of abatement is best achieved. We return to this issue when we have described our macroeconomic climate model. We end this section with the following summary.

Conclusions 1:

i) The uncertainty around the consequences of emissions of CO_2 *and other greenhouse gases is very large and very difficult, if not impossible, to quantify objectively.*

ii) Calculations of the social cost of carbon and optimal carbon taxes based on cost-benefit analysis are fraught with so much uncertainty that they are hard to use as a basis for policy prescriptions. We do not think that this state of affairs will change materially over the foreseeable future, even with continued efforts within climate science and the area of damage measurement.

iii) Given the consensus around the basic mechanisms and around the quantitative uncertainty surrounding them, we consider good climate policy to be a "robust" one where significant reductions of emissions are implemented now, with a zero net global emissions target somewhere in the beginning of the second half of the present century.

A quantitative global climate-economy model

We will now describe a simple integrated assessment model. It is, like Nordhaus's DICE and RICE models, neoclassical in its core, which means that---by proper parameter calibration---can be made consistent with stylized facts on the historical process of economic growth.[13]

By insisting on matching the key aggregate features of the historical data, we follow the same procedure as do climate modelers. Our setting is described in detail in Hassler, Krusell and Olovsson (2021a).[14]

We certainly do not want to claim that our model cannot be improved upon. However, we do believe that it gives us a reasonable benchmark, along with preliminary indications of key orders of magnitude. Overall, the model is quite closely related to Nordhaus's DICE and RICE models, but whereas DICE/RICE

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[13] It should perhaps be added that accounting for the historical macroeconomic data on inputs and outputs using the neoclassical growth model is not only possible but the only way that macroeconomists, so far at least, have been able to proceed successfully.

[14] The results here come from a re-calibrated version of the model there; in particular, we now incorporate the results from Folini et al. (2021).

are chiefly optimal growth frameworks, our setting is formulated as a market economy and hence straightforward to use for positive analysis of policy and welfare calculations.

The model contains 8 regions, but we also consider a one-region world. One of the 8 regions produces conventional oil, which it sells at a competitive global world market. This region has no other production and is the only producer of conventional oil. We simplify by assuming that the price of conventional oil only affects scarcity: conventional oil is in limited supply and is costless to extract.[15] This region is calibrated to represent the OPEC countries and Russia. The remaining 7 regions represent Europe, the United States, China, South America, India, Africa, and Oceania. They all produce a single final good that is non-tradable. The aggregate production function is Cobb-Douglas in capital *K*, labor *L*, and energy services *E*. Output $Y_{i,t}$ in region *i* in period *t* is produced competitively and satisfies

$$Y_{i,t} = A_{i,t} L_i^{1-\alpha-\nu} K_{i,t}^{\alpha} E_{i,t}^{\nu} \qquad (6)$$

where $A_{i,t}$ is TFP that is exogenous to region *i*. Hassler, Krusell and Olovsson (2021b) shows that directed technical change in energy efficiency historically has responded to energy prices in a way that makes the income share of energy roughly constant in the long run, thus motivating the Cobb-Douglas specification we apply here. Hassler, Krusell and Olovsson (2021b) also shows that energy is highly complementary to capital and labor in the short run and even well approximated by a Leontief technology in a capital-labor composite and energy. Since the focus here is on the long run, we adopt the Cobb-Douglas specification and merely note that in order to assess the short-run consequences of taxes or other policies we would need a richer model of production in the short run.

We assume catch-up by making $A_{i,t}$ grow faster in China, South America, India, Africa, and Oceania. In particular, we assume that China converges to a balanced growth path with approximately twice the GDP of the EU and the United States, whereas India and Africa both converge to a path with the same GDP as the EU and the United States. The speed of this transition is set so that around 25% of the productivity gap is closed each decade.

Energy services are produced competitively with firms using a nested CES production function using different energy sources. One region, the U.S., has access to non-conventional oil reserves (fracking), which is combined with conventional oil, to produce an oil composite. This nest has a high elasticity of substitution (10) within it. In a second nest, the oil composite is combined with coal and green energy to produce energy services $E_{i,t}$ with a lower elasticity of substitution (2 in most of the exercises). The supply of conventional oil comes from the oil-producing region and the other fuels are produced regionally at a constant, but possible time varying, unit cost. An additive, region-specific carbon tax is applied to the use of conventional oil, fracked oil, and coal. Taxes are returned as negative income taxes

[15] We assume that the oil-producing region cannot invest its wealth abroad. This is unrealistic but makes the model much simpler to solve. We do not think this simplification has major influence on our results compared to a model where foreign investment of oil incomes are allowed within some limits. Allowing perfect international capital markets would produce highly counterfactual current account balances.

to the representative household in each region. When we introduce carbon taxes, we always assume that the tax per unit of carbon grows at the same rate as the GDP trend.

As mentioned above, there is a world market for oil and trade balance is imposed; hence, we abstract from intertemporal trade across regions. Trade in coal and green energy can be allowed but has no other consequence than aligning the production costs of these energy sources.

The preferences of the representative household in each region are given by

$$E_t \sum_{s=0}^{\infty} \beta^s \ln\left(C_{i,t+s}\right)$$

where $C_{i,t}$ is aggregate consumption in region *i* in period *t*. The assumption of logarithmic consumption preferences is in line with what is used in typical quantitative macroeconomic models. Here, we adopt this functional form mostly in order to simplify our computations.

Finally, we use the carbon-climate model described in the previous section and a damage function expressed in "excess atmospheric CO_2", i.e., the difference between the current and the pre-industrial level, as discussed in Golosov et al. (2014). This implies that total factor productivity is

$$A_{i,t} = e^{z_{i,t} - \gamma_i \tilde{S}_{t-1}}$$

where $\tilde{S}_{t-1} \stackrel{\text{def}}{=} S_{t-1} - S_0$ is carbon in the atmosphere in excess of the pre-industrial level at time *t*-1 and γ_i is a region-specific climate damage sensitivity.[16] $z_{i,t}$ is the exogenous productivity factor whose trends are selected for every i as discussed above; the initial levels are chosen so as to equalize the initial marginal products of capital across regions.

Our assumptions are stark but we argue that they are defensible. They imply that the model is close to trivial to solve since the decision rules turn out to be very simple. In particular,

1. the saving rates of the representative households in all oil-consuming regions are constant and equal to $((\alpha\beta)/(1-\nu))$;
2. the supply of conventional oil from the oil-producing region is perfectly inelastic at $(1-\beta)R_t$, where R_t is the remaining stock of oil reserves;
3. the fuel mixes and the prices of energy services satisfy closed-form expressions in the underlying prices of the energy sources (of which only the world market price of conventional oil is endogenous);
4. and the prices for other inputs (e.g., wages and rental rates for capital) are set to equal their respective marginal products.

[16] The use of $\tilde{S}_{t-1}$ for period *t* productivity here is more convenient for solving the model numerically than using $\tilde{S}_t$. $\tilde{S}_t$ moves very sluggishly, so the results would barely change if we used $\tilde{S}_t$ instead.

The only variable that does not have a closed-form solution in our model is the world market price of conventional oil. As noted above, the income and substitution effects of future oil prices on oil supply cancel in the forward-looking optimal supply of conventional oil, thus making the supply perfectly inelastic. The demand for oil, on the other hand, has no forward-looking components. Thus, solving for the equilibrium oil price is a static problem of finding a solution to one equation in one unknown. Thus, we can even use Excel in solving the present model, which is not an argument for the model from a scientific perspective but it makes it very useful for teaching, including at an undergraduate level. Finding the optimal tax is more challenging, but as we have argued above, finding the optimal tax for a given set of assumptions is not very policy-relevant, given the large Knightian uncertainty and given that current taxes on carbon, despite an agreement to act, are still close to zero on average at a global scale. The practical relevance of the present model instead comes from using it to study the positive implications across of a larger set of policy possibilities.

We base our baseline damage coefficients on Nordhaus and Moffat (2017) that map the global mean temperature into damages. Using a climate sensitivity of 3, we reformulate the damage estimates as functions of the CO_2 concentration rather than temperature. We assume twice as high a sensitivity in Africa and India, with the caveat that these numbers, again, are just best guesses. Most of the other parameter values are standard. We calibrate production prices of coal and the stock of oil so that prices are roughly in line with data at the starting point of the simulation. The oil price is 70 USD per barrel. The production costs for fracking and coal are 40 USD per barrel and 74 USD per ton, respectively. Calibrating the cost of using green energy is challenging since this category consists of a large variety of different energy sources. We set it so that the price is equal to that of oil at the beginning of the calibration. The exogenous production costs are kept constant over time while the oil price is endogenous.

We calibrate the starting values of the variables in (6) so that the distribution of output and CO_2 emissions match the data, as seen in Figure 9.

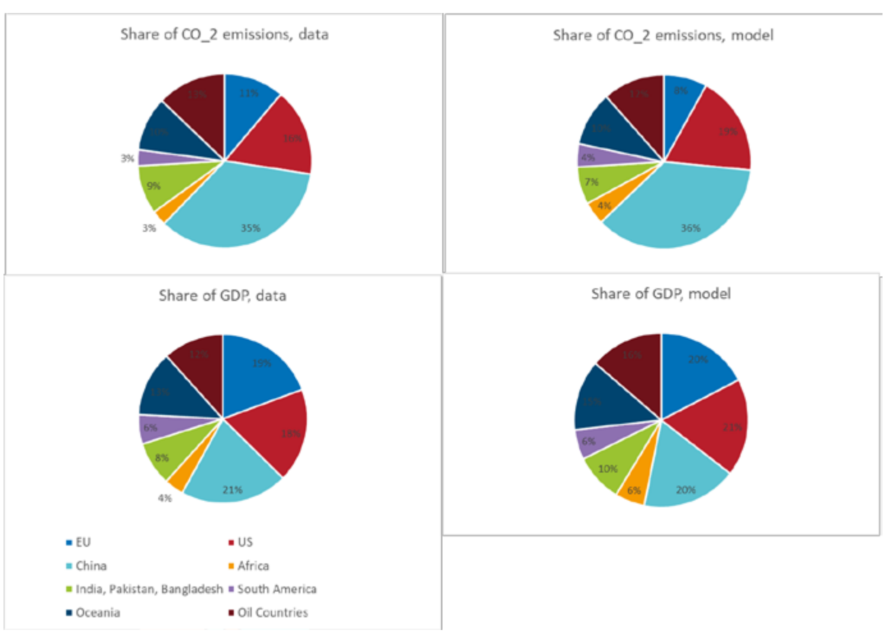


Figure 9. Model contributions to Global GDP and CO_2 emissions. Source: Model in Hassler, Krusell Olovsson (2021).

Policy, policy mistakes, and their consequences

We now use the model to study the effects of policy. We will analyze a number of scenarios and use them to derive a number of results. As we have emphasized above, we do not argue that these in any way are final and quantitatively exact. We do believe, however, that they give indications of orders of magnitude that should be taken seriously.

The effects of different degrees of abatement

Our first experiment is to introduce a modest global carbon tax, set at a level equal to the price of emission allowances in the EU/ETS before the reforms of this system that were recently decided upon. The tax we use is thus 20 euro per ton of CO_2. For an interpretation of this number, note that the combustion of a liter of gasoline produces around two and half kilos of CO_2 and that one kWh of coal-powered electricity leads to one kilo of CO_2. Thus, the tax corresponds to around 5 cents per liter (20 cents per gallon) of gasoline and 2 cents per kWh of electricity. Thus, we think of this as a modest tax. However, as we see in Figure 10, the tax has a substantial effect on emissions.

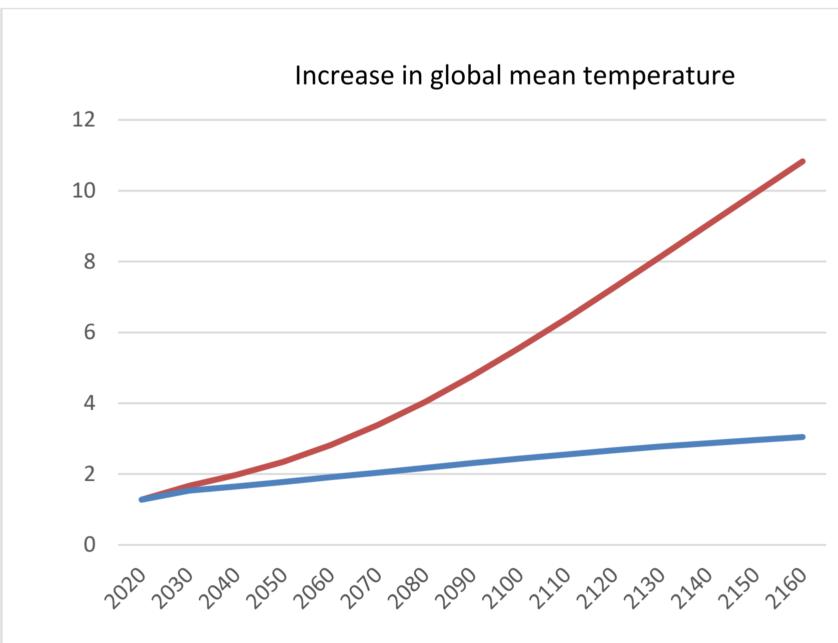


Figure 10. Global warming under business as usual and a modest emission tax.

This delivers our first quantitative result (we will use the term "tentative" to emphasize the need for further research).

Tentative result 1: *A carbon tax (a price on emissions) is a potent policy tool to reduce emissions.*

Next, we study the consequences of a forced phase-out of fossil fuel, roughly in line with the Paris agreement. Our production function does not allow a complete phase-out since oil and coal are necessary for production given our calibration. Instead, we force emissions down linearly from the current emission levels of around 40 $GtCO_2$ per year gradually to 4 and assume that these remaining 4 units can be removed by carbon capture and storage (CCS). The gradual reduction is assumed to be linear and is chosen so that the cumulative global emissions are 775 $GtCO_2$. The implied emissions per decade are thus 351, 242, 133, and 47, respectively, until carbon neutrality has been achieved. Recall that the assumptions we have made imply that the supply of oil is inelastic. All oil will thus be used up; the only way to affect the path of the supply is to tax it at a sufficiently high rate that the producer price of oil is zero in every period. This result, we think, is reasonable, given that the current profit per unit of oil is so high. The implication is that emissions per period are bounded from below by (1-β) times the remaining oil reserves. We use OPEC's estimate of the remaining oil reserves, 1,190 billion barrels, as representing the amount of conventional (zero extraction cost) oil still in the ground. This corresponds to 500 $GtCO_2$, which is two thirds of the carbon budget we allow in the experiment. The space for using coal and fracking is thus quite limited as a result.

Figure 11 shows the difference between global GDP under the phase-out and GDP in the business-as-usual scenario. The key take-away is that the costs of the phaseout are limited: only around one percent of GDP. Towards the later part of the century, there are gains, but as we have discussed above, these gains are highly sensitive to the climate sensitivity to emissions and the sensitivity of damages to temperature, about both of which we have very limited knowledge at present.

In the analysis we also find that additional revenues from the carbon tax, expressed as a share of GDP are relatively modest. They peak at a bit above 1.5% of GDP in 2050. One the one hand, this is not a large share and it does not point to substantial energy scarcity. On the other, given that emissions at that time are low, just above 10% of current emissions, the carbon tax per unit of emitted CO_2 is quite high. However, recall our argument for allowing 10% of current emissions permanently. We assume these emissions can be handled with CCS. Then, these emissions will not be taxed. Under the arguably reasonable assumption that CCS is cheaper than the 2050 carbon tax, we are exaggerating the private costs of emissions.

Here, we need to re-emphasize that the initial losses in output are likely larger given that the short-run elasticity between energy and other inputs is much lower than unitary as assumed in our model. Costs would also be higher if the long-run elasticity of substitution between green and fossil energy is lower than we assumed and at the same time the supply elasticity of green energy is lower. Furthermore, it is important to note that large investments in new energy infrastructure are needed in order to make the transition possible without large consequences for GDP. IEA (2021) provides an estimate of how large these investments need to be in a scenario that takes the world to climate neutrality by 2050. Their estimates imply that the current total investment share (total investments as a share of GDP) need to go up by around two percentage points by 2030. This is certainly a quite substantial increase. However, it is not historically exceptional. The global investment share 2010-19 was 24.4% while it was almost two percentage points higher during the period 1970-1999 at 26.1%. Nevertheless, the increased investment rate must impact consumption negatively even if GDP is not affected.

Various political frictions could also increase costs. Here, we want to mention uncertainty about future climate policy that may impede the willingness of private actors to make front-loaded capital heavy investments. The production of green energy also has negative local externalities that can prove difficult to compensate for and then leading to local popular resistance. Even if a green transition can have acceptable costs, it is clear that it could also be very costly.

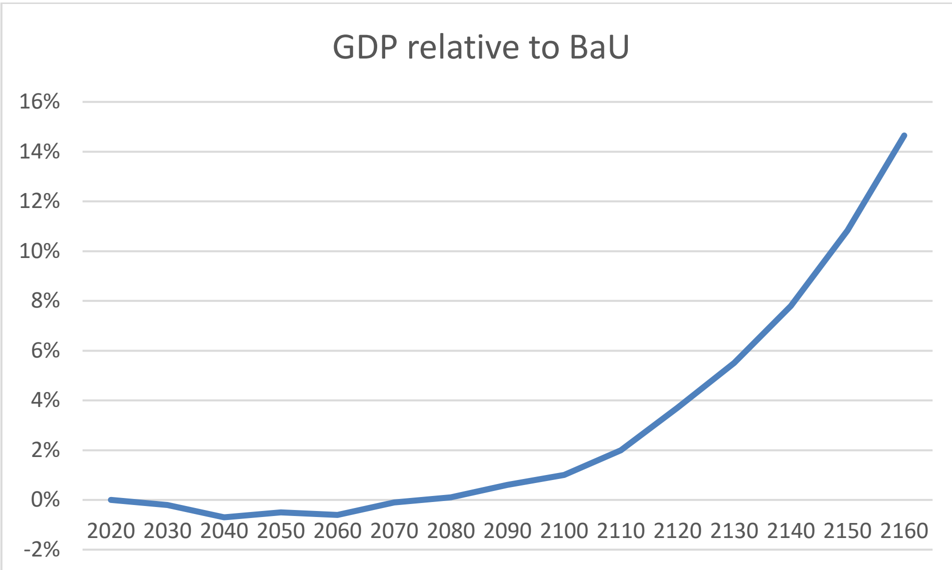


Figure 11. Effect on Global GDP from a fast phase out of fossil fuel.

We summarize as follows.

Tentative result 2: *A smooth transition to climate neutrality at 2050 can be accomplished at a fairly small cost in terms of lost GDP. However, large investments in green energy infrastructure will be required. A badly designed transition can turn out be very costly.*

Policy errors, I: a global tax at the wrong level

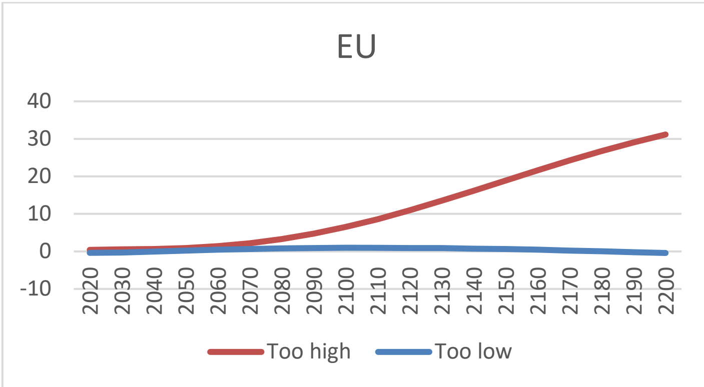
We now turn to "policy errors". We define these in comparison with our model-implied optimal policy, which is a carbon tax set at the same level per unit of carbon in all parts of the world and whose value---according to the Pigou principle---should equal the marginal externality damage costs at all points in time. As noted in Conclusion 1, of course, as consequence of the large Knightian uncertainty, we are far from sure of what these optimal tax values are. However, we can still consider departures from the Pigou tax that are plausible---in the sense that they have been implemented or at least form part of serious proposals---and easy to analyze quantitatively given our model, which allows welfare comparisons quite straightforwardly. A "robust" policy is thus a policy that, for a large set of plausible parameter values, produces small costs relative to what *ex post* would have been optimal, had the parameter values been known. There is a large literature on formal methods for finding robust policies. Here, we merely illustrate based on work in Hassler, Krusell, and Olovsson (2018, 2021a).

We begin by defining a set of possible damage sensitivities taking into account the uncertainty discussed in Section 2. We use the IPCC's likely range for climate sensitivity. We also use the data underlying

Nordhaus and Moffat (2017)'s meta-study on global climate damages to calculate a range of likely climate damage sensitivities. We then define two extreme policy mistakes:

1. **Hoping for the good, but ending up with the bad**. Here we calculate an optimal tax given a parameterized model, thus using the formula in Golosov et al. (2014), based on the assumption that the climate sensitivity is at the lower end of IPCC's likely range and that the damage sensitivity is at the lower end of the range we calculated based on Nordhaus and Moffat (2017). The implied optimal tax is barely above zero (which is consistent with the current global tax average!). We then use this tax in the model under the assumption that the assumed sensitivities are instead at the upper ends of their respective likely intervals. We use our model to calculate the ex-post cost of this policy error expressed as a share of consumption flow.
2. **Planning for the bad, but ending up with the good.** This is the opposite policy mistake. The tax is now calculated under the assumption that the two sensitivities are at the upper ends of their respective likely ranges. The truth then turns out, ex post, to again be at the opposite ends of the likely intervals, so that the ambitious climate policy was in fact introduced in vain.

Figure 12 shows the regional costs of the two policy mistakes. As we see, in most cases there is a stark asymmetry between the two policy mistakes. It is not very costly to have introduced an ambitious climate policy in vain. The opposite, not having introduced it when it would have been needed, turns out to be substantially more costly. Note that in this scenario, climate change induces damages also under the optimal policy and what is depicted in Figure 12 is the additional cost of not having introduced the policy that turns out to be optimal. Clearly, the asymmetry between the policy mistakes would have been larger, likely very much larger, had we also included scenarios deemed unlikely by the IPCC, for example tipping points in the global climate. This would not have affected the cost of policy mistake 2, but would increase the cost of policy mistake 1 in major ways. The asymmetry is less pronounced for the U.S., and absent for the first half of the simulation.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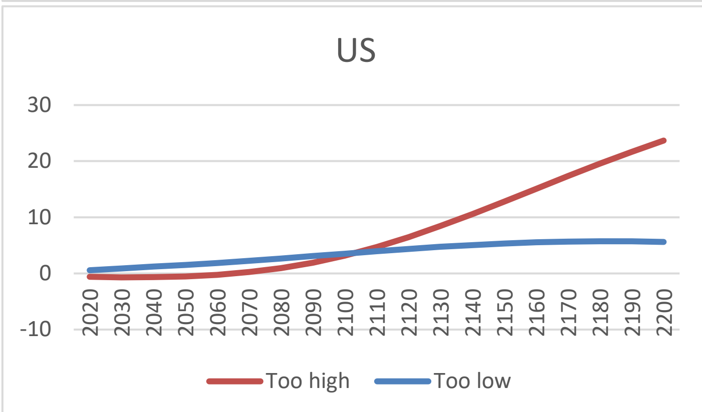
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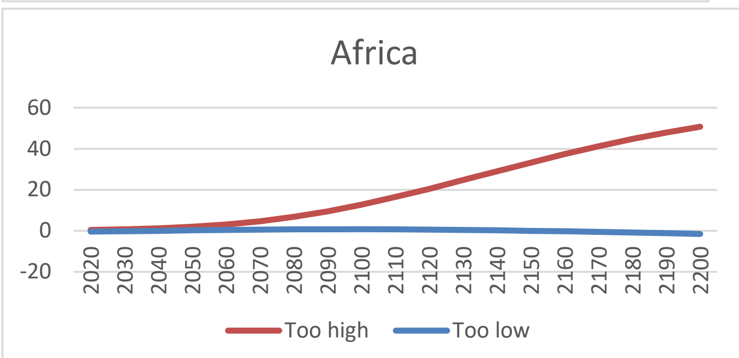
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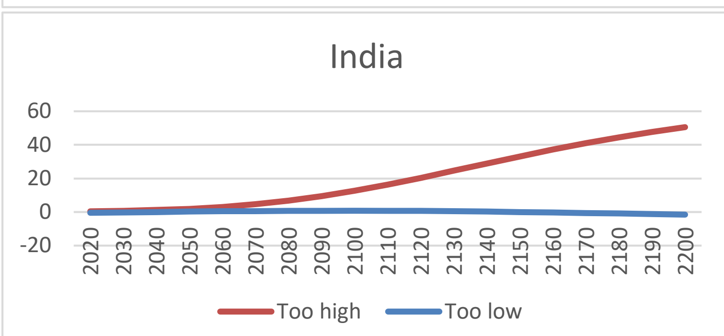
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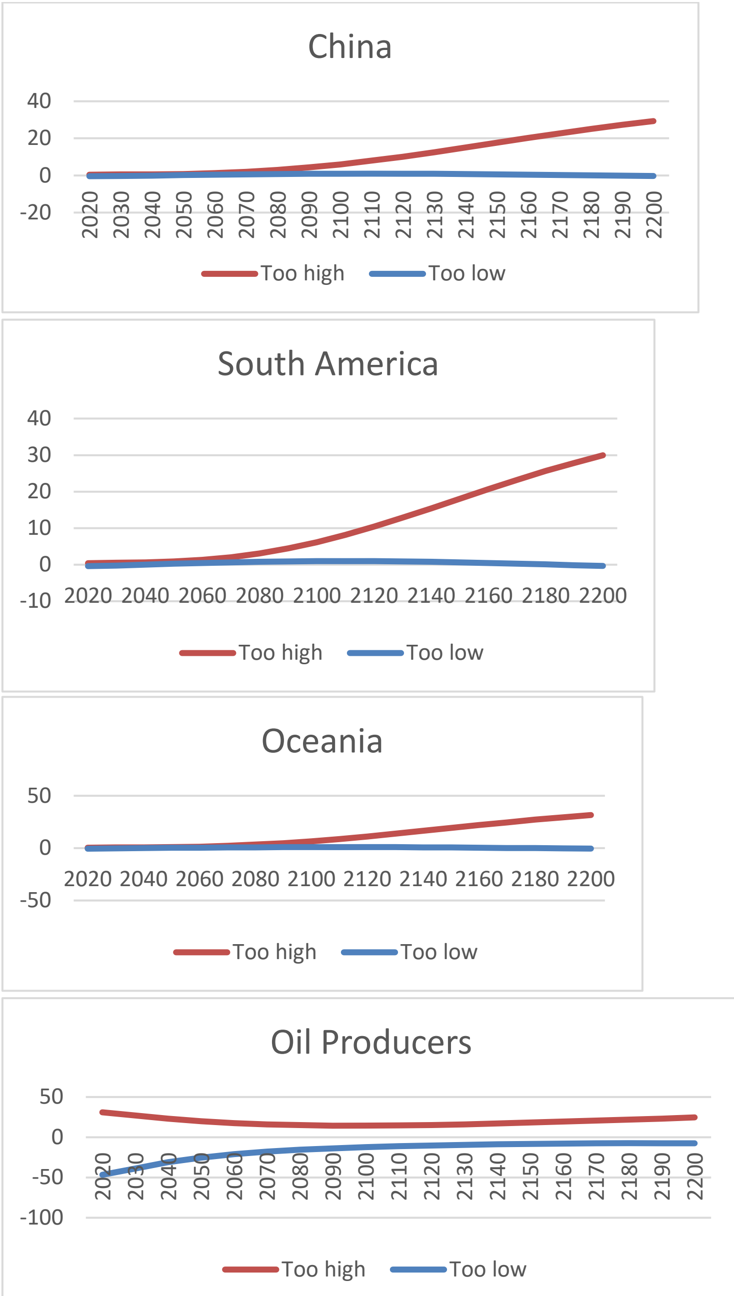

Figure 12. Regional costs of policy mistakes 1 (too low taxes) and 2 (too high taxes) by region.

These confirm the overall picture of a large asymmetry except in the U.S. case. This is explained by our assumption that the U.S. has an unlimited supply of fracked oil which can be used at a cost of 40 USD per barrel. Under the ambitious climate policy, these reserves are used much less than what is optimal (for the U.S. and for the world). The assumption of unlimited relatively cheap oil reserves in the U.S. is made out of computational convenience mainly so we are aware that this particular model implication is not entirely robust.[17]

Finally, it is obvious that the oil producing region loose from a taxation in vain. It is a transfer to the consumers. However, this is small in comparison. The global asymmetry of the costs of the two policy mistakes is very large. This is shown in Figure 13.

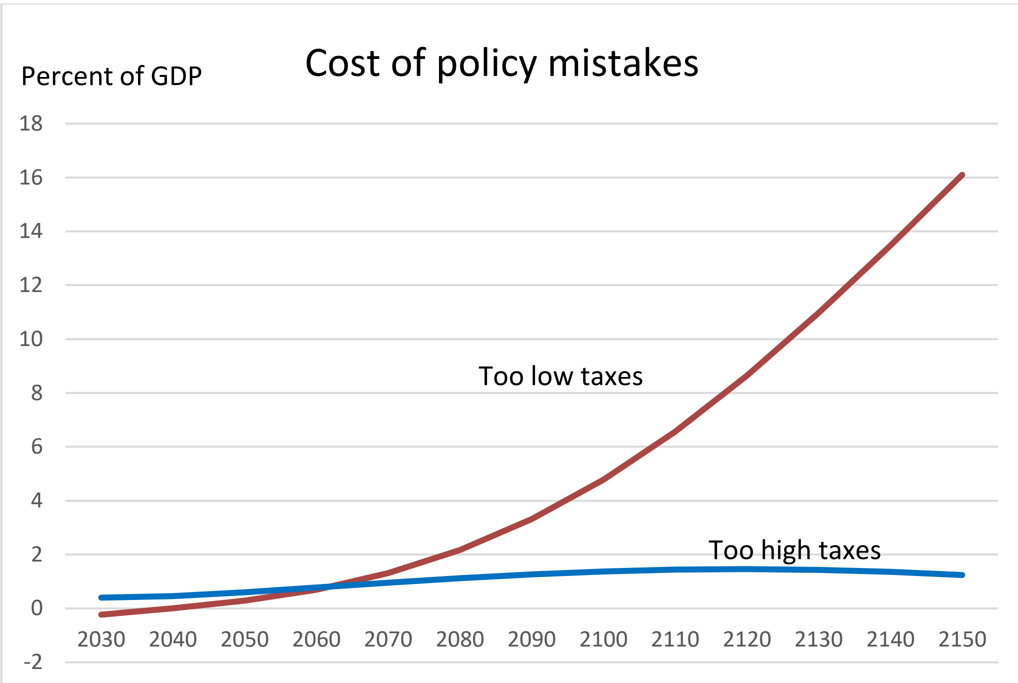

Figure 13. Global costs of policy mistakes 1 (too low taxes) and 2 (too high taxes) by region.

Tentative result 3. *An ambitious climate policy is a robust policy: it offers cheap "insurance" against high sensitivities of climate to emissions and damages to climate change.*

Policy errors, II: departing from global coverage

We now turn to the issue of global coverage of the climate policy. Specifically, we ask how costly it would be if some regions of the world do not participate in taxing carbon, while others compensate by using higher carbon taxes. We start with a global climate policy that is moderately ambitious, i.e., based on relatively low uniform global carbon tax.[18] With a climate sensitivity in the middle of the IPCC range, it would imply global warming at 2.6 degrees 150 years from now. We then select a set of regions for which carbon taxes are set at zero, while taxes are raised in the remaining regions, uniformly, so as to

[17] Our model can easily handle energy sources whose prices are either only pure scarcity rents or only reflect production costs. The range in between requires a numerical solution of the model which certainly is doable, but left for future research.

[18] It is calculated as the carbon tax that would be optimal for intermediate values of the sensitivities discussed above.

meet the same final temperature. We start with assuming that India and Africa do not participate. The welfare costs in consumption equivalents are shown in the upper panel of Figure 13.

We see that India and Africa gain but also that the other regions lose: they lose much more than India and Africa gain. The large losses for the remaining regions derive from having to impose carbon taxes that are five times as high as in the case with globally uniform taxes.

Next, we consider the case when China is not participating. Here, it turns out that even if taxes are set infinitely high in the rest of the world, the target will be exceeded. We thus somewhat arbitrarily set the Chinese carbon tax to 15% of the uniform tax, in which case it is possible to compensate for the low Chinese tax and still limit warming to 2.6 degrees. However, the remaining regions then need to implement a tax that is twenty times higher than in the uniform case. This is extremely costly in consumption terms, which is shown in the lower panel of Figure 14.

Figure 14. Welfare costs of less than global taxation.

The explanation for the costs of non-uniform taxation is that the marginal cost of taxation increases in the rate. Clearly, the marginal cost is zero at a tax rate of zero. As we show above, a low tax rate is, on the other hand, quite effective in reducing emissions (see Hassler, Krusell and Olovsson, 2021a, for more detail on this result, which we consider to be quite robust). We thus have the following.

Tentative result 4: *A successful climate policy requires that all regions of the world participate. Compensating for significant-size regions failing to phase out fossil fuel is very costly, or outright impossible.*

Policy errors, III: subsidizing green technology instead of taxing carbon

In the policy discussion, it is sometimes argued that subsidies to green energy, or the development of green alternatives, can be used as a substitute for carbon pricing. In our present model, technical change is exogenous so we cannot directly study the consequences of subsidies to R&D. However, we can analyze and compare different assumptions on the growth rates of the production costs of the elastic sources of energy (coal and green). In our benchmark calibration, we have assumed that the prices of coal and green in terms of the final good are constant over time. This can be interpreted as representing a uniform technological growth rate affecting the final good as well as the production of energy services. However, green technologies are in fact becoming cheaper rather fast, both due to market forces and subsidies. Therefore, we look at a few alternative scenarios to our baseline case. We assume, first, that technological change in the green energy sector is about twice as fast as in the rest of the economy, implying that the relative price of green energy falls by 2% per year. We also study the consequences of halting technical change in the coal sector so that its relative price increases by 2% per year.

The results for the global economy are depicted in Figure 15. As a benchmark, we include the case with neutral technical change and a modest global carbon price (purple curve with circles). We see that a fast growth in green technology, involving falling prices of green energy, is not an effective substitute for carbon pricing (lower panel). In fact, emissions and the global temperature increase somewhat faster even than in the business-as-usual scenario. On the other hand, a stagnant brown technology, involving relative prices of coal that increase over time (black dashed curve), turns out to be a fairly effective substitute for carbon pricing, also if is it is combined with faster green growth (blue curve with circles). With fast green technology growth, the world uses much more energy, and that is good for growth. But this result comes with no climate benefits.[19]

[19] For very high elasticities, this result should reverse, since if green and brown energy sources were perfect substitutes, only the cheapest one would be used, so that once green energy becomes cheaper than brown energy, there is a complete and rapid switch.

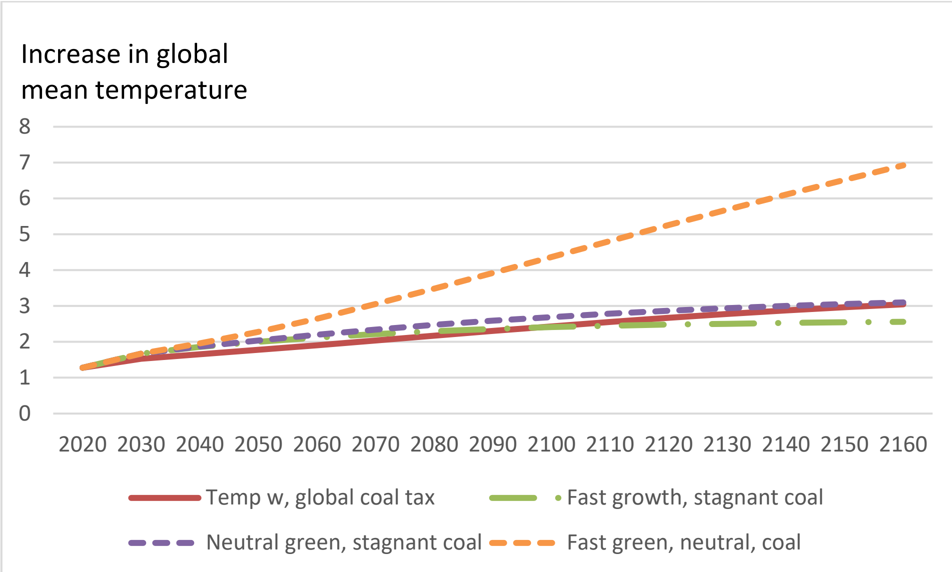

Figure 15. Climate change with different technological growth rates in the green and brown energy sectors.

Policy discussion

In our model, there are no explicit frictions or other market failures than the climate externality. Because of this, nothing more than a carbon price is needed in our model. In the real world, in contrast, many other policies are likely to be required. It is convenient to classify these in three groups, with distinct purposes. We argue that good policies from all three policy groups are critically required.

1. Policy tools aiming to directly limit CO_2 emissions. These can be in the form of a carbon price, implemented either by a tax on emissions or by cap-and-trade. Also, direct regulation, like banning particular technologies is in principle possible.
2. Tools aiming to overcome various economic and political frictions that can make the transition to climate neutrality induced by group one policies too socially, economically and/or politically costly. Here, subsidies, free allowances, redistribution of various kind as well as industrial policies are examples.
3. Policies aiming to induce other countries/regions to participate in the climate transition.

It should here be noted that although the three policy groups are complementary in achieving the overarching goal of make the world climate neutral, policy evaluation needs to be different across them. Specifically, it is natural to measure effectiveness of polices in group one in terms of cost per ton of abated emissions or simply by how much emissions reductions are achieved. In group two, this is not the right way and sometimes even impossible. If a cap-and-trade system is used to limit emissions (a tool in group one), policies in group two cannot affect emissions, since they are determined by the cap. Instead, policy group two tools need to be evaluated in terms of how well they remove frictions and facilitate the build-up of green alternatives to the fossil that are phased out by the group one tools.

The European example and IRA

On June 30, 2021, European climate neutrality by 2050 became binding European law. A reduction of emissions by 55% compared to 1990 to be reached by 2030 was also included in the European Climate Law. Just before this agreement, the European Commission had presented a plan for how to reach these targets: the Fit-for-55 plan. For this plan to become binding, an agreement between the European Parliament and the European Council, which represent the governments of the member states, must be reached. When this article is written, agreements on almost all the elements of the proposal have been reached and these involve a plan very close to the original proposal. Only some details remain to be finalized. There are three pillars in the policy package: (i) a faster reduction in the number of emission allowances allocated every year in the existing EU Emission Trading System (EU ETS 1; (ii) a new cap-and-trade system for heating and land transportation, EU ETS 2; and (iii) a faster reduction in the ceiling on the average CO_2 intensity of new cars and vans, reaching zero by 2035.

We argue that these three pillars accomplish what is required when it comes to polices in group 1, i.e., they imply very reasonable limits on emissions of CO_2 within in the European Union for the entire future. To appreciate this point, we need to describe the package.[20]

The first pillar in the package concerns the EU ETS 1. This is a cap-and-trade system that covers about 15,000 firms in heavy industry such as steel and cement production, power, air transportation with the EU, and from 2024 also shipping within the EU. Within the system, 43% of the allowances are distributed free of charge to participating firms and the rest is auctioned out. There is a liquid market for the allowances that can be saved for later use. Firms in the system must every year surrender an allowance for each ton of greenhouse gases it emitted. The system covers close to 50% of the unions CO_2 emissions.[21] The number of emission allowances allocated to the market every year falls over time in a linear way implying that zero will be reached in finite time. The speed of reduction has been increased by reforms in 2009 and 2018. The agreement on the Fit-for-55 package almost doubles the yearly reduction relative to the previous rules, from 43 to 84 million tons between 2024 and 2027, and fully doubles it, to 86 million tons, thereafter. The reduction rules have been decided for the period until 2030. If the reduction continues at the same speed thereafter, no allowances will be allocated after 2039, as shown in Figure 16. From 2020 until then, emission allowances corresponding to approximately 17 $GtCO_2$ will have been allocated.[22] This puts a strict limit on emissions for all the covered industries. Steel and cement plants, power production, air lines, and shipping that have not adopted emission-free technologies will therefore need to shut down. In addition, the distribution of free emission allowances will be gradually phased out.

[20] See also Flam and Hassler (2023).

[21] Other greenhouse gases, such as methane and NOX, are largely outside the system, particularly in agriculture. In terms of total emissions of greenhouse gases measured in CO_2 equivalents, EU ETS covers around two fifths (38.5% in 2019).

[22] Previously issued and saved allowances are included in the calculation.

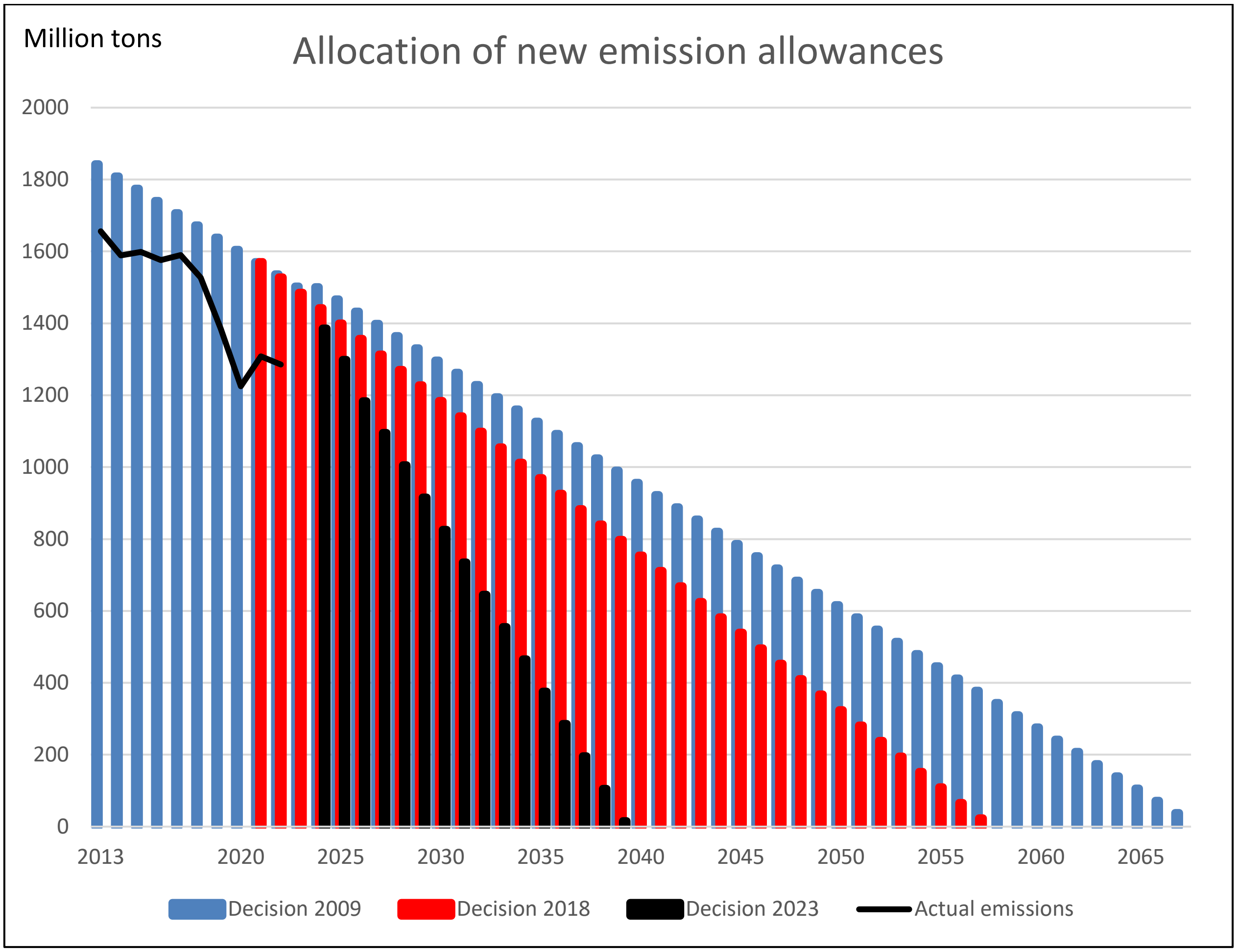

Figure 16. Allocation of new emission allowances in EU ETS 1. Source: Nilsson (2023).

The second pillar is the introduction of a second cap-and-trade system, EU ETS 2. This will cover almost all CO_2 emissions outside of the EU ETS 1, in particular occupational heating and road transportation. The main noteworthy exception is for agriculture, where methane and NO_{x} are the main greenhouse gases emitted; these emissions are not covered. It is important to note, however, that cumulative carbon budgets are not relevant for these other greenhouse gases since for them, it is the flow of emissions that drive climate change, not the cumulative emissions (unlike for CO_2), since they only stay in the atmosphere for a short period of time. The decentralized and small-scale production of these other greenhouse gases also poses different control challenges than do the large-scale and centralized distribution system for fossil fuels. It is therefore reasonable to leave agriculture outside of the emission trading systems. The EU ETS 2 will start in 2027 and the number of emission allowances auctioned out every year will fall and reach zero in 2042 provided the decided reduction rules are not changed.[23] After 2042, fossil fuels will then in principle be forbidden in the union. Under the proposal, around 7 $GtCO_2$ will

[23] There is a provision to postpone the introduction to 2028 if oil and gas prices are sufficiently high in 2027.

be emitted within EU ETS 2. The number of yearly allocated emission allowances are depicted in Figure 17.

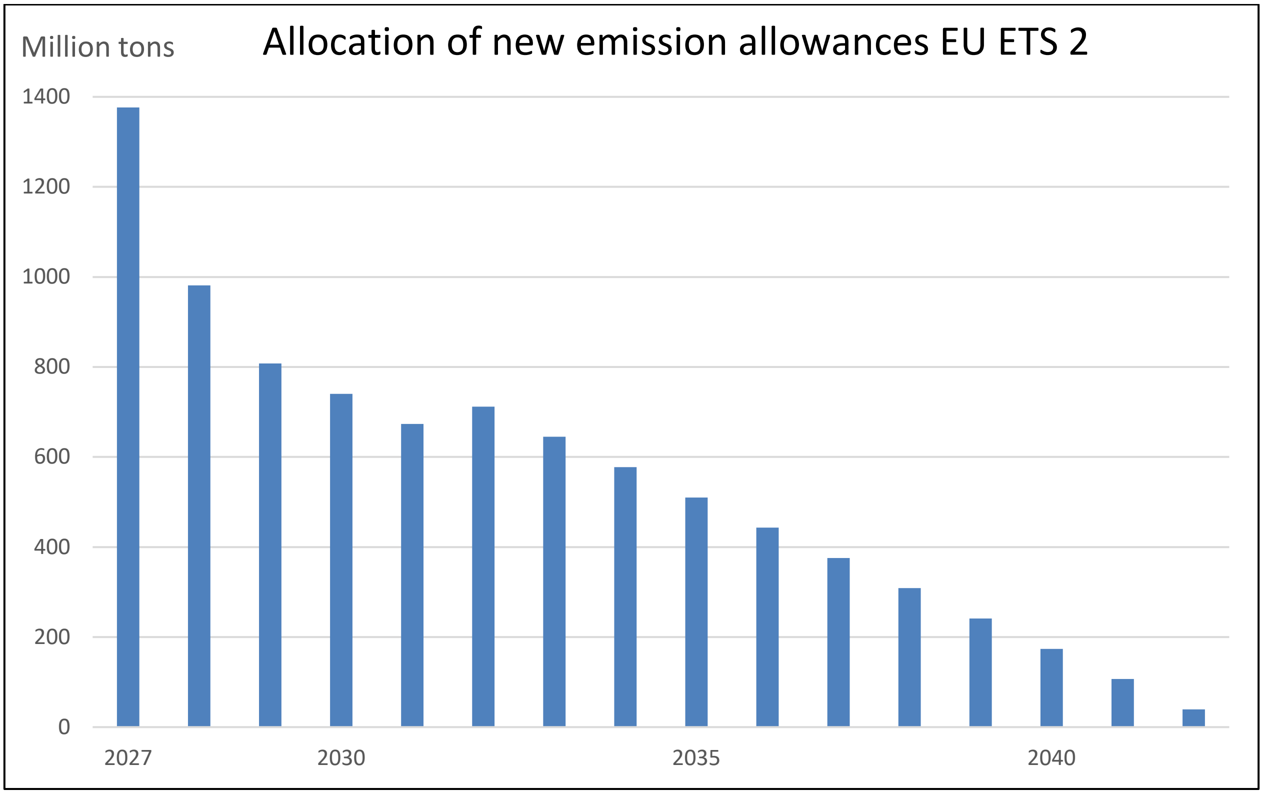

Figure 17. Allocation of new emission allowances. Source: Nilsson (2023).

The third pillar in the decision is a tightening of the policies already in place regulating CO_2 emissions for new cars and vans. The average CO_2 intensity per manufacturer is currently capped at 95 gram CO_2 per km. This ceiling is to be lowered gradually and will reach zero in 2035. Manufacturers whose cars emit less than the ceiling, e.g., Tesla, can sell their over-performance to other manufacturers. After 2035, new cars that can run on fossil fuel will be forbidden.

Compared to carbon taxes, an emission trading system provides an exact control over the cumulative amount of emissions. This may have a pedagogical advantage when dealing with CO_2 emissions. Another advantage is that by controlling the quantity, there is no spillover risk to global emissions.[24]

Since EU ETS 1 and EU ETS 2 will cover almost all CO_2 emissions, it is immediate to calculate the cumulative emissions from EU over all the future. Given that the decided rules for phasing out the distribution of new emission allowances are kept unchanged approximately 34 $GtCO_2$ will be emitted

[24] In a setting where, as in the real world, multiple jurisdictions decide on climate policy, Mideksa (2022) shows that the global outcome is more efficient if each jurisdiction sets the quantity of emissions rather than the price (tax).

from 2020 and over the entire future. With 450 million EU citizens, this is 75 ton per capita. If all countries of the world did the same, global accumulated emissions would be 600 GtCO. This is close to the carbon budget for 1.5 degrees and far below that for 2 degrees warming.

Thus, EU does what is required according to the Paris agreement when it comes to limiting its own emissions. The Paris agreement also requires that the richer countries take a wider responsibility for the global transition to climate neutrality. But for EU to do this by a substantially faster phasing out of emissions is very expensive for EU and not very helpful for the poorer countries. Instead, this responsibility needs to be taken by other means, in particular technological and financial transfers. In conclusion, the Fit-for-55 package essentially accomplish what is required under policy group 1. What remains is to adopt other policies so as to make the transition smooth, i.e., policies in group 2 and, finally, whatever it takes to bring the rest of the world on board.

The U.S. has chosen a different climate strategy with the Inflation Reduction Act of 2022. The backbone of the policy package consists of large subsidies to non-fossil energy production, transmission, and storage, to green infrastructure, and investments in energy efficiency. A key purpose is to increase the supply of non-fossil energy and reduce its price. Our analysis above suggests that subsidies to green energy is not sufficient for phasing out carbon emissions, at least not sufficiently fast. Instead, policies from group 1 are needed. A climate strategy that starts with policies in this group are likely politically impossible in the U.S. at the present time. This is particularly the case if carbon taxes, or the revenues from an emission trading system, accrues to the federal government. However, it is possible that the subsidies to green energy paves the way for later regulation that directly curbs the use of fossil fuels. We argue that the best way to do this is an emission trading system. Direct regulation might work, but it may be substantially more complicated to implement than an emissions trading system. The optimal speed with which fossil fuels ought to be different in different parts of the economy; in an emission trading system or with carbon taxes, the market steers the allocation: it determines where the phase-out will be faster. With direct regulation, this need to be decided by the regulator.

Going forward: research needed

We argued above that the task of finding the optimal carbon price will likely not lead to credible and policy relevant results. This also means that we do not see damage measurements under business as usual as key inputs into decisions on mitigation policy. Damage measurements, however, are important for understanding where adaptation is needed and what kinds of adaptation will work. (It is theoretically possible that low-cost adaptation can keep damages at a minimum, hence making mitigation policy unnecessary. We regard this view as highly hazardous and therefore abstract from it.) Thus, with mitigation in focus, damage measurements are not central.

We therefore argue that the macroeconomic focus should be on improving the inputs into the policy discussion aiming at answering the *how* question. What would be of great value, in particular, is further insights on how different policies affect the economy, both as far as their efficacy in lowering emissions and their economic costs. Our model shows that a transition to global climate neutrality over, say three decades, is a robust policy, i.e., it is not expensive and may turn out to be highly valuable. More confidence in the conclusion that such a policy is not very costly would be highly policy relevant also without generally agreed upon estimates of the consequences of business as usual. We believe that this work must involve both theory and econometrics, and ideally, they would go hand in hand. How easily various alternative energy sources can be used, instead of fossil fuel, is another key issue. In our model, the complementarity between fossil fuel and green energy sources in production plays this role, together with their respective cost parameters. Relatedly, it would be valuable for us to get better estimates of the cost structures for different kinds of fossil fuels (extraction and refinement). It is also quite likely that the answers to these questions are very different in different parts of the world, so although it is important to adopt a global approach to how to best mitigate, it will likely be very important to allow for regional heterogeneity.

Sufficient popular support for the transition to climate neutrality is necessary for it to happen. Most likely, this will require a broad palette of policies, including industrial and regional policies as well as redistribution. Research with the aim of establishing where important frictions exist and how they could be overcome to make the transition smooth would be highly valuable.

Finally, a transition to climate neutrality over, say, three decades may turn out to be insufficient. Very high climate sensitivities outside the range we considered here, as well as global tipping points in the carbon-climate system, are not likely, but impossible to completely rule out. Global cooperation might also break down implying a return to something closer to the old business as usual. Because of this, plan B:s should also be developed. Such plans would most likely involve large-scale geoengineering such as in Fuglesang and Hassler (2023).

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