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24-x The macroeconomics of climate change

Starting points, tentative results, and a way forward

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ABSTRACT

This paper provides scientific starting points for climate-economy modeling. The sensitivity of climate change to emissions of greenhouse gases is uncertain. The same is true about the long-run economic consequences of climate change. Therefore, we argue that traditional cost-benefit analyses including calculations of optimal carbon taxes are, and will remain, unconvincing. Climate-economic models are nevertheless useful for finding effective climate policies that are robust to different assumptions about these uncertainties. This paper outlines such a model. A key result is that a transition to climate neutrality can be implemented at an acceptably low cost. We discuss the policies required for this transition, compare climate policies in the European Union and the United States, and provide suggestions for future research.

JEL codes: Q54, E1

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Introduction

This paper outlines some important starting points for climate-economy modeling, provides some tentative results, and draws policy conclusions from them. We end with a discussion of the kinds of research needed going forward.

In environmental economics, and economics more generally, the study of climate change is attracting an increasing amount of research. A broad consensus has been built around the notions that (1) emissions of carbon dioxide and other greenhouse gases drive global warming and (2) 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 reports of the Intergovernmental Panel on Climate Change (IPCC). The second point also comprises research by natural scientists but here economists are making important contributions as well. There is significant uncertainty on the two points, as the understanding of the carbon cycle and the climate system is limited by open questions about magnitudes as well as mechanisms, and the systematic quantification and study of damages from climate change in the short- and long-run around the world is really just in its infancy.

Climate change is a slow process and emissions of carbon dioxide affect the climate for hundreds of years. The consequences for the economy and human welfare in general over such a long period cannot be forecast with any precision. The fact that these uncertainties are large and unlikely to vanish is central to our policy conclusions. We argue that it is not possible to rule out devastating consequences of continued greenhouse gas (GHG) emissions at the current rate. Thus, for precautionary reasons humankind needs to do something about climate change: specifically, emissions must be limited. If it can be established that a transition to climate neutrality need not be overly costly, such a transition is the way forward. This point of view implies that the key task going forward is to describe how such a transition can achieved. This is more policy relevant than calculating costs of business as usual under debatable or speculative assumptions.

Some observers appear to think that the question of *how* to achieve a low-cost transition is not so critical and that, rather, everyone, countries and individuals, should simply make a maximal effort to stop emissions to the very best of their abilities. This effort, to the same observers, often tends to take the form of calls for a complete change of lifestyle, in many cases for growth to stop, and in a few for a change of economic systems away from markets toward central planning. We find this view 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 “minimal effort,” but of course subject to attaining the same goal. The reason is simple. The less people think about the efficiency of stopping climate change, the more costly we fear it will be, and the more costly it is, the higher the likelihood that the policies required to end climate change will be voted down (in democracies; or, in nondemocracies, abandoned for lack of party support). Thus, to us, cost efficiency is the crucial subject to study in this area.

The study of cost efficiency in combating climate change is an area in which economists, in principle, should excel. After all, cost efficiency is a key part of what economists do (and what other scientists do not focus on). Economists have the tools and a reasonable starting point. As in most other areas of economics, the question at hand is fundamentally quantitative. Thus, it is not sufficient to just say “follow Pigou,” especially since carbon taxes are barely implemented anywhere in the world, despite the decades-long recommendations of economists. It is thus necessary 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 the use of appropriate quantitative inputs in the analysis. Without them, the analysis will remain abstract, whereas policymakers need 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 literature on climate policy but merely assert that much of the research is lacking at least one of several key quantitative inputs. One such is knowledge of the most up-to-date assessments of the natural science of climate change and in particular the reduced-form linear link between cumulative emissions and warming. Another concerns the degrees of uncertainty in various parameters, including those relevant in damage measurements. Other important facts include estimates of the stocks (locations, extraction/refinement costs) of various forms of fossil fuel; knowledge about alternative sources of energy services (e.g., green technology, nuclear options); and 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 European Union, including among climate commentators in the region. 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.

In the second part of the 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 section discusses some weaknesses of our analysis, which needs to be addressed when designing a complete climate policy package. We discuss actual climate policy in the European Union and the United States and provide some suggestions for future work.

Quantitative Starting Points

This section covers what we consider key facts to take into account in any analysis of climate policy. We begin with the natural-science part. Here we draw on reports from the IPCC and show a convenient summary of it based on William Nordhaus’s work. We then turn to estimates of the remaining amounts of fossil fuel in the ground in relation to global emissions. Next comes a discussion on uncertainty: aspects of the climate system where science is far from a complete quantitative understanding. Then we review economic damages, interpreted broadly to include all direct and indirect effects on humans. Also here, uncertainty is very large.

Relationship 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

Earth's surface cannot directly radiate to space. Instead, it transits 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 (this happens on average at around 6,000 meters). With more carbon dioxide (CO_2) and other greenhouse gases, the heat must travel to higher altitudes 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 leaves 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. That heat leaves the body in a less efficient way implies that it becomes warmer below it. A thicker blanket therefore leads to a higher steady-state temperature below it. In the same way, a higher GHG concentration creates a thicker "blanket" around Earth, which raises the steady-state temperature below the blanket, i.e., on Earth's surface.

The greenhouse effect triggers a large number of feedback effects, in both the climate system and 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 (1994) for his DICE/RICE models replicates the dynamics of the most advanced Earth System Models very well (Folini et al. 2024). It is therefore of value to describe it here.

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 preindustrial values:

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

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

The right-hand side of equation (1) contains an expression consisting of three terms in the brackets: $\frac{\eta}{\ln 2} \ln\left(\frac{S_{t-1}}{S_0}\right)$, $-\kappa T_{t-1}$, 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 (S_t) that drive climate change. The changes are calculated from their respective preindustrial levels and are measured in watts per square meter (W/m^2). 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 in the brackets in equation (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 preindustrial amount. This term is called *CO_2 forcing* in the literature.[1] It has long been known (Arrhenius 1896) that a good approximation of the strength of CO_2 forcing is that it is proportional to the logarithm of the ratio of the current concentration and its preindustrial value. The parameter η is set to 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.[2]

The second term in equation (1) captures the fact that as Earth warms, more energy is radiated into space. The effect is approximated to be linear in T_{t-1} with a proportionality constant set to κ = 1.06. The third term represents the cooling effect that arises if the ocean is cooler than the atmosphere. This term is also approximated to be linear, namely in the temperature difference between the atmosphere and the ocean $(T_{t-1} - T^L_{t-1})$.

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 $(T_{t-1} - T^L_{t-1})$. 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, heating of the oceans is much slower than that of the atmosphere. In the equations, this is captured by the parameterization that $\sigma_1\sigma_2 >> \sigma_3$. Because of this, a given temperature difference $(T_{t-1} - T^L_{t-1})$ has a larger effect on the speed of change in the atmospheric temperature than on the change in ocean temperature (and with opposite signs).

The dynamic system described by equations (1)-(2) is stable. It is straightforward to show 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).[3] The latest IPPC report states a best guess for the ECS of 3°C per doubling of the CO_2 concentration.

The second module in the model is a description of the 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 measured in billions of tons of carbon (GtC).[4] The other two reservoirs, also measured in GtC, are the biosphere and the surface ocean (combined), denoted S^U_t, and the deep oceans, S^L_t. It is necessary to have these two additional reservoirs in the model because the carbon circulation 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 the size of the source reservoirs and emissions are denoted by E_t:

$$S_t - S_{t-1} = -\phi_{12}S_{t-1} + \phi_{21}S^U_{t-1} + E_{t-1} \quad (3)$$
$$S^U_t - S^U_{t-1} = \phi_{12}S_{t-1} - (\phi_{21} + \phi_{23})S^U_{t-1} + \phi_{32}S^L_{t-1} \quad (4)$$
$$S^L_t - S^L_{t-1} = \phi_{23}S^U_{t-1} - \phi_{32}S^L_{t-1} \quad (5)$$

[1] Another term used for the same thing is *radiative forcing*.

[2] To understand 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*10¹⁵ W to Earth's energy budget. This is close to the power of two million nuclear power plants (currently about 440 are in operation).

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

[4] A ton of carbon (C) produces 3.66 tons of CO_2 when combusted.

Together, equations (1)–(5) describe the relation between emissions E_t and climate change, as represented by the global mean atmospheric temperature at ground level.[5,6]

As noted, this compact system shows a surprisingly good accordance with the most advanced Earth System Models (Folini et al., 2024). Based on the IPCC, Mikhail Golosov et al. (2014) present a summary description of the carbon cycle that remains valid. They describe the carbon cycle as having three important characteristics: (1) about half of the emitted CO_2 leaves the atmosphere within a few decades, (2) between one fifth and a quarter stay for thousands of years, and (3) the remainder leaves the atmosphere with a half-life of a few hundred years. CO_2 emitted by human activities 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 than that of CO_2 since the decay is approximately geometric with a half-life of 9 years. Because methane leaves the atmosphere relatively fast, it is largely the flow of methane emissions that affect the energy balance. To incorporate the effect of methane in the model, an additive methane forcing term can be added within the parentheses of equation (1). Sometimes this is simply assumed to be proportional to the CO_2 forcing. Obviously, this is quite arbitrary for, in particular, long simulations.

Many other factors influence the energy balance. Important human-induced forcing effects are due to aerosol emissions. These have direct effects on the energy balance but indirect effects, particularly by affecting cloud formation, are very important. Here, however, forcing is largely negative, producing a cooling effect. This effect is currently estimated to be about as large as methane forcing, thus balancing the latter.[7] However, the uncertainty about the strength of aerosol forcing and its consequences for the climate is very large. The IPCC (2021) states that "other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C."[8] Since this cooling effect will fade fast after the burning of fossil fuels comes to an end, this uncertainty is problematic. We will return to how uncertainty affects policy recommendations below.

We summarize the discussion so far with the following observation:

Observation 1. *A simple system of 5 difference equations describes the relation between emissions of CO_2 and global warming quite well both qualitatively and quantitatively.*

Production- and Consumption-Based Emissions

Current global emissions of CO_2 are almost 40 $GtCO_2$ per 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 European Union and United States,

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[5] The parameters are set to $\sigma_1 = 0.137, \sigma_2 = 0.73, \sigma_3 = 0.00689, \eta = 3.45, \kappa = 1.06$, 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 $T_{2015} = 1.078, T^L_{2015} = 0.3132$, $S_{2015} = 850, S^U_{2015} = 765$ and $S^L_{2015} = 1799$.

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

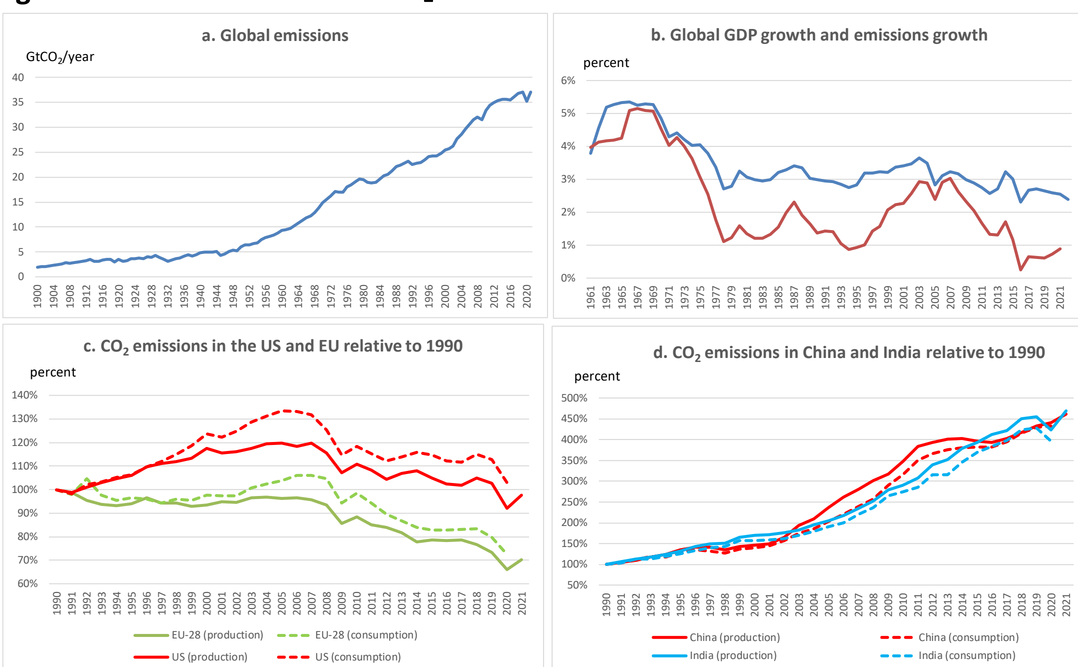
[7] See figure 7.6 in IPCC (2021) for the strength of different components of the overall forcing.

[8] Statement A.1.3, Summary for Policymakers, IPCC (2021).

on the other hand, emissions have fallen over the last two decades. It is sometimes conjectured that this decline is due to carbon leakage, i.e., the relocation of carbon-intensive production to countries with more lax climate policies, in particular 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 associated with the production of the goods used for consumption and investment 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.

Panel c of figure 1 shows EU and US production- and consumption-based emissions. Although the consumption-based measures started falling a few years later than their production-based measures, the trends of the two series have been very similar since 2008. Conversely, in China and India emissions have increased dramatically, with similarly parallel trends for the two emission measures (panel d).

Figure 1 Various measures of CO_2 emissions



Note: The series in the top right panel represent 9-year centered moving averages.
Sources: Our World in Data 2023 and World Bank National Accounts.

Observation 2. *Global CO_2 emissions are not falling, but they are increasing at a lower rate than two decades ago. Both consumption- and production-based emissions have fallen in the European Union and United States over the last two decades, whereas the opposite is true for emissions in China and India.*

Stocks of Fossil Fuel

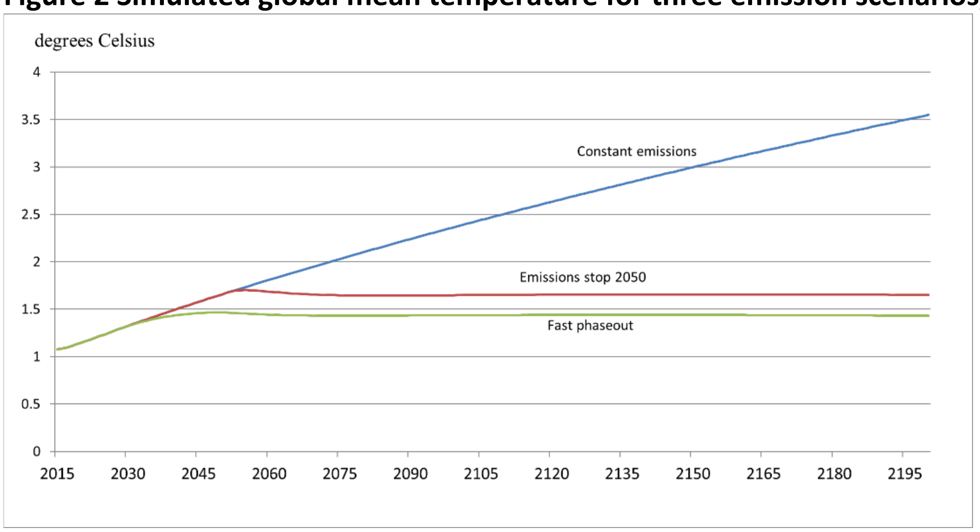
How much fossil fuel remains in the ground is uncertain and depends on how it is classified. A common classification is “proven reserves,” interpreted as known reserves that are profitable to recover with current technologies and prices. Obviously, prices and technology change, and with them the amount 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. The IEA (2022) provides estimates for proven reserves and resources: for oil, 202 and 715 GtC, respectively; for natural gas, 112 and 412 GtC, respectively; and for coal, 753 and 14,562 GtC, respectively.[9]

Of the proven reserves of oil and natural gas, some are very cheap to extract. This is the case for much or most of the oil in the Middle East, which is half of total reserves. Reserves with low extraction costs have a low long-run supply elasticity because they are profitable to extract also with low producer prices. These reserves will likely be extracted eventually. Carbon taxes and other policies affecting demand will affect the timing of extraction but not the long-run cumulative extraction. The quantity of these low-cost reserves is uncertain, but as a benchmark in our calculations we assume that the amount of fossil fuel with extraction costs that are negligible relative to the market price is 140 GtC, corresponding to 500 $GtCO_2$. This is approximately half of the proven reserves for oil and natural gas. In our simulations, these reserves will eventually be extracted regardless of the level of carbon taxes.

Using the 5-Equation Model

Let us now use the 5-equation model described in equation (1)-(5) to describe three hypothetical scenarios, of which two lead to climate neutrality.[10] In the first scenario emissions simply continue at the current rate of 10 GtC/year; in the second they continue at 10 GtC/year until 2050 and then fall to zero; and in the third 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, 2015–2195



Source: Authors' calculations.

[9] Oil is measured in barrels, natural gas in m^3, and coal in tons. To convert to GtC, we used the following conversion factors: 7.33 barrels of oil/ton, with a carbon content of 84.6 percent; natural gas 0.511 kg carbon/m^3; and the carbon content of coal is set to 70 percent.

[10] The model is very easy to implement in a spreadsheet.

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. 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 for very long time (by a fixed amount). This is a key insight from natural science illustrated by our simulation. It is relatively recent (Allen et al. 2009) but has gained broad recognition.

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

A second message is that, 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 of emissions 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. The IPCC (2021) calculates the remaining carbon budget from the start of 2020. The estimates are 137 and 369 GtC corresponding to 500 and 1,350 $GtCO_2$, for a 50 percent chance of staying below 1.5°C and 2°C global warming, respectively. This should be compared to the estimates of reserves and resources of fossil fuel still left to extract.

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

A third message is that observation 3 runs counter to the popular belief that the global climate system is close to a tipping point, when the relation between emissions and climate change abruptly and perhaps irreversibly changes. The IPCC report on the Physical Science Basis states that "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, 202).

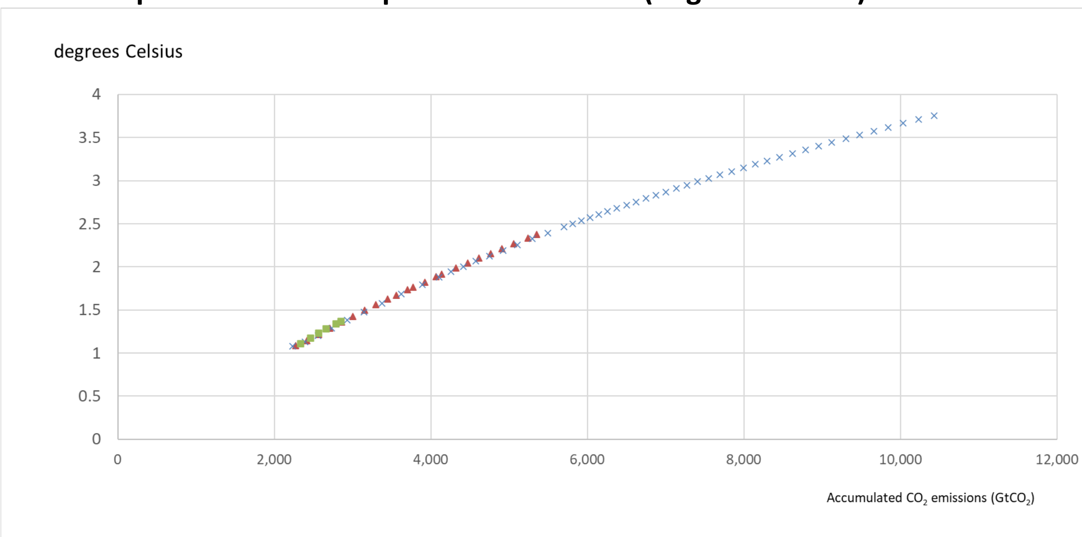
The linear relation between cumulative emissions and global mean temperature applies to both historic and future emissions, at least for scenarios up to three times the current amount of cumulative emissions. For predictions of the relation going forward, the IPCC uses different emission scenarios and different Earth System Models.[11] The approximative linearity is also a result of the model described above in equations (1)–(5). This is depicted in figure 3 for three different emissions scenarios: a linear phaseout of emissions to 2050 (squares), constant emissions at current rates (10 GtC/*y* = 37 $GtCO_2$/yr) until 2100, and increasing emissions at 2 percent per year until 2100. The last scenario is a fairly extreme one, in which emissions at the

[11] For a graphical depiction of the linearity between cumulative emissions and temperature, see figure TS.18 in IPCC (2021), available at https://www.ipcc.ch/report/ar6/wg1/figures/technical-summary/.

end of the century are five times larger than currently. For all the scenarios, the starting point is the amount of cumulative emissions in 2015 at 2200 $GtCO_2$ and a temperature increase of 1.08°C, all measured with respect to preindustrial levels.

Different models used by the IPCC produce different proportionality coefficients while being consistent with historic observations.[12] We will return below to this uncertainty, which will be key for our policy conclusions. It is also important to note that we are discussing the global mean temperature. Regional tipping points are likely and will have differential impacts.[13]

Figure 3 Relation between accumulated emissions (in gigatons of CO_2, $GtCO_2$) and global mean temperature rise over preindustrial levels (degrees Celsius)



Note: Green squares represent a linear phaseout to 2050, red triangles constant emissions at 37 $GtCO_2$/year until 2100, and blue crosses growing emissions reaching 200 $GtCO_2$/year in 2100.
Source: Simulations from the model described in the text.

The result from observation 3, that the temperature stays constant after the accumulation of emissions ends, can be understood by examining equation (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 in parentheses must be zero and remain zero. That the temperature remains constant implies that the second term, the outflow of energy to space $(-\kappa T_{t-1})$, is constant. However, the first term, 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 because of the slow removal of CO_2 from the atmosphere. The third term, the cooling effect from oceans $\left(-\sigma_2(T_{t-1} - T_{t-1}^L)\right)$, is also falling in absolute value since the oceans are slowly heating up. Since σ_3 is low, this is a slow process. Purely by coincidence, 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.

[12] An important difference between different models is their quantification of temporary effects due to aerosols.
[13] For example, "At the regional scale, abrupt changes and tipping points, such as Amazon rainforest dieback and permafrost collapse, have occurred in projections with Earth System Models" (IPCC 2021, 202).

Returning to the analogy of greenhouse gases as a blanket. Suppose a person gets into a bed with a blanket and a mattress that initially is cold. Suppose also that overt time the blanket becomes thinner, reducing its warming effect. On the other hand, the cooling effect from the mattress falls as it is heated up. The temperature below the blanket can then stay approximately constant.

The discussion so far describes the evolution of the global mean temperature. It is, of course, not this measure that affects 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. Because warmer air can hold more humidity, precipitation increases, including its extremes. The IPCC (2021) provides model predictions of the association between the global mean temperature and the predicted frequency and intensity of extreme weather events. The relation is fairly linear, implying that as CO_2 emissions keep accumulating, the frequency and intensity of extreme weather events increase.[14] It is important to note, however, that the uncertainty is very large. Taking this into account, we arrive at another summary observation.

Observation 5. *The frequency and intensity of key weather extremes increase with the global mean temperature. The predicted increase is gradual and approximately linear, but the uncertainty is very large.*

Uncertainty

The linearity result discussed above is quite useful for modeling and for policy analysis. However, the usefulness is reduced by the large uncertainty around the point estimates of the proportionality coefficient in the relation between cumulative emissions and the increase in the global mean temperature. The IPCC (2021) specifies a likely uncertainty interval of 1.0°C/TtC to 2.3°C/TtC with a best estimate of 1.65°C/TtC.[15] The proportionality coefficient is called the *Transient Climate Response* (TCR) and represents the final increase in temperature after a path of increased atmospheric CO_2 concentration. Using quasi-experimental methods, Giselle Montamat and James Stock (2020) come to very similar quantitative conclusions about the TCR. It should be noted that the confidence intervals for the TCR should not be taken as representative of climate consequences on a centennial scale, where the uncertainty is even larger.

A key source of uncertainty surrounding the consequences of CO_2 emissions is associated with the equilibrium climate sensitivity (global warming per doubling of the CO_2 concentration). In terms of the simple model described above, the uncertainty is about the parameter κ that quantifies the relation between global warming and the outflow of energy to space. The IPCC (2021) provides a “likely” confidence interval for the equilibrium climate sensitivity of 2.5°C to 4°C and a “very likely” interval of 2°C to 5°C.[16] It explains that one should

[14] See figure TS.12, panel a-d, IPCC (2021), available at https://www.ipcc.ch/report/ar6/wg1/figures/technical-summary/.

[15] A Tt is 1000 Gt. The interval corresponds to 0.27°C/TtCO_2–0.63°C/TtCO_2, with a best estimate of 0.45°C/TtCO_2 (statement D.1.1, Summary for Policymakers, IPCC 2021).

[16] Statement A.4.4, Summary for Policymakers, IPCC (2021).

interpret "likely" as implying a 2/3 probability and very likely as a 90 percent probability. There is also a substantial amount of uncertainty around how much warming humans have already caused. The IPCC states it to likely be between 0.8°C and 1.3°C.[17]

To gauge the range of the uncertainty, we note that the accumulated amount of emissions since 1850 is estimated to be 650 GtC (i.e., 0.65 TtC). Using the uncertainty interval for the proportionality coefficient relating cumulative emissions and temperature we can easily compute an interval for the likely global warming caused by emitting the same amount going forward (which would take around 65 years at the current global emission rate): It would likely be between 0.65°C and 1.5°C. Adding this to an uncertain starting point produces large uncertainty in estimated temperature projections.

These simple examples use the likely uncertainty intervals. The IPCC does not rule out either much higher or much lower climate sensitivities. Furthermore, the linearity result is uncertain beyond the current century, especially if the temperature increases more than 2°C. 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 judgment-based assessment of many sources of information, including both simulations and historical data. Thus, it is not possible to provide objective probability measures, in particular for more unlikely possibilities, such as for climate sensitivity to exceed 5°C. The uncertainty around such possibilities is 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 given at 1.5°C to 4.5°C in the fifth IPCC report, which is wider at both ends than the range in the sixth report (2.5°C to 4.0°C). Over a longer perspective, however, it is not clear that uncertainty is falling. In the first IPCC report, published in 1990, the range was also 1.5°C to 4.5°C, and this range was given in the second and third reports; it shrank slightly to 2.0°C to 4.5° in the fourth report.[18]

Observation 6. *The uncertainty around the relation between emissions and climate change is large, essentially Knightian, and unlikely to vanish.*

The Relation between Global Warming and Welfare

There is now a fairly large and quickly expanding literature on the economic consequences 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 across all relevant mechanisms as well as over time and across space. Such an aggregation is a formidable endeavor. Relatively few aggregate studies are undertaken, but two metastudies are available (Nordhaus and Moffat 2017, Howard and Sterner 2017). The results of the latter study, including the authors' best aggregation, are shown in figure 4. It shows the relation between

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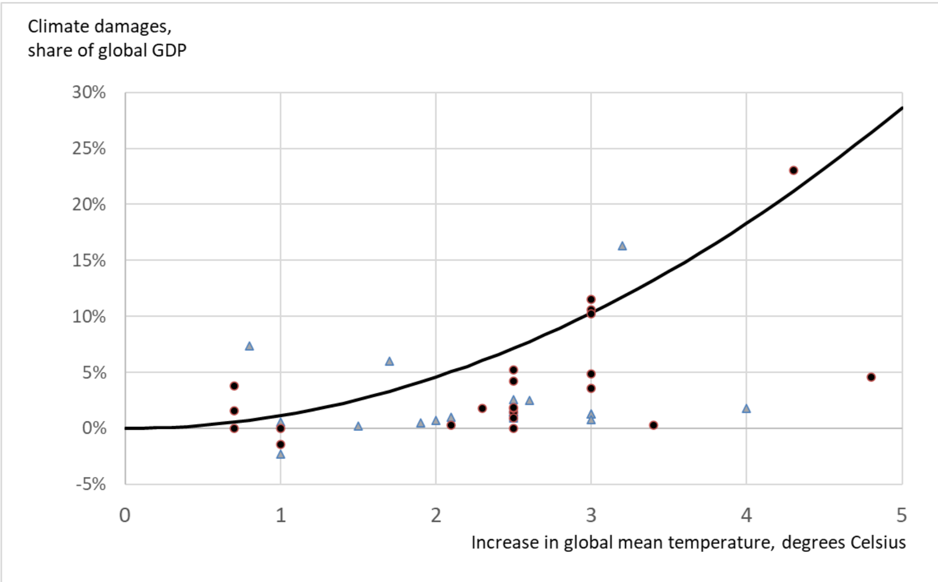
[17] As noted, a key source of uncertainty is the strength of the cooling effect of atmospheric aerosols caused by humans.

[18] See figure TS.16, Technical Summary, IPCC (2021), available at https://www.ipcc.ch/report/ar6/wg1/figures/technical-summary/.

the increase in the global mean temperature and aggregate global climate-related damages converted to monetary terms and expressed as a share of global GDP.

Figure 4 Metastudy of climate damages from increased global mean temperature, share of GDP



Note: Dots are individual studies and triangles are variations of previous studies that are given less weight in the aggregate relationship depicted by the solid line.
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 statistical regressions where aggregate variables such as GDP or mortality are projected onto observed weather averages over intervals of time. Although one should think of changes in the climate as more or less permanent changes in the distribution of weather events, shorter, natural weather variations may 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 effects of a permanently warmer climate.

There are two advantages of the reduced-form approach. First, it directly aggregates all potential mechanisms behind the relation between climate change and 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 by Marshall Burke, Solomon Hsiang, and Edward Miguel (2015), a study much used in the literature and by organizations as the International Monetary Fund:

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

where $\Delta y_{i,t}$ is the GDP growth rate and $T_{i,t}$ is temperature 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 estimate 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.[19]

By aggregating over countries, a global aggregate climate damage function can be constructed. Burke, Hsiang, and Miguel (2015) provide such an aggregation, which is approximately in line with the preferred metastudy aggregation in Howard and Sterner (2017). The problem with the Burke et al. (2015) study, however, is that its implications at national levels are hard to take seriously. We examined the effects of the estimates of β_1 and β_2 on national outcomes by feeding in the projections of changes in EU-15 national temperatures on a path that leads to global warming of 2.5°C by the end of the century (a temperature scenario similar to what is expected under current global commitments to climate policy). We found that the estimates imply an enormous divergence in GDP impacts, because colder countries very much benefit from climate change while warmer ones lose in terms of growth rates.

Over time these differences accumulate to very large differences in the level of GDP (figure 5). Sweden would be more than five times richer with climate change than without, and Finland would gain even more. Portugal, on the other hand, would lose 32 percent of its GDP. That these effects would materialize is difficult to believe. Moreover, these extreme effects of average temperature on GDP are hard to square with the current relationship between temperature and output in Europe: 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 their average temperatures.

The other type of study, using the bottom-up approach, first specifies a set of mechanisms through which climate change can affect the economy. Then for each mechanism and geographic 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 by Nordhaus (1994). Few similar studies have been produced since his work. A recent and much more detailed study is the PESETA[20] IV report (European Commission 2020). It 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 study only the European Union and United Kingdom. The baseline is a scenario where climate change affects the 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 6 shows the effects in five EU regions as well as for the aggregate.

The effects in figure 6 are small overall. They are somewhat higher in the southern parts of the European Union, where damages are dominated by increased mortality in association

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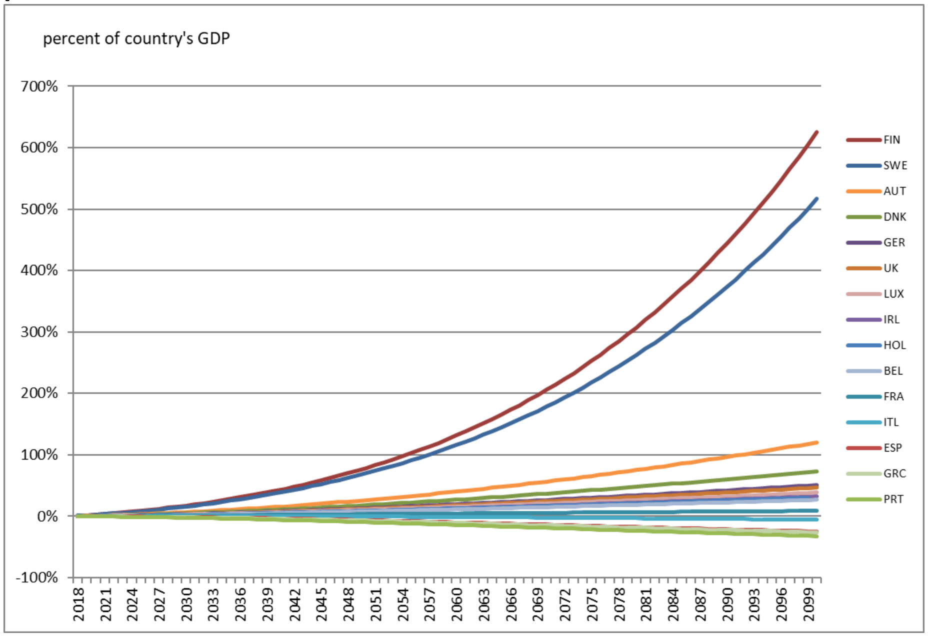
[19] In the baseline specification of Burke et al. (2015), β_1 and β_2 are estimated at 0.0127 and 0.0005, respectively.

[20] PESETA = Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis

Figure 5 Effects on GDP of a gradual increase in the global mean temperature to 2.5°C above preindustrial level



Note: We assume an exogenous path of global warming where the global mean temperature increases at a smoothly falling rate that reaches zero in 2070. Then the global mean temperature has increased by 2.5°C relative to the preindustrial level and is constant thereafter. We then construct national temperature paths, taking into account that different geographic locations are differentially sensitive to changes in the global mean temperature. These sensitivities are derived from statistical downscaling of data from high-resolution global circulation models. This method uses output from these models as data and regresses the change in local temperature on the global mean temperature. The regression coefficient then describes the estimated change in the local temperature per unit of change in the global mean temperature. We use the following values for these coefficients: SWE 1.44, FIN 1.56, DNK 1.17, GER 1.10, FRA 0.97, UK 0.89, HOL 0.93, ESP 1.19, PRT 0.92, IRL 0.78, ITL 1.12, AUT 1.17, BEL 0.93, LUX 1.03, and GRC 1.01. These all represent the statistical downscaling coefficient for the location of the national capital. At any point in time, the increase in the national temperature is given by the increase in the global mean temperature times the national coefficient of sensitivity. The starting temperature in 2018 is the average temperature over the period 1960–2015 plus half the increase in the global mean temperature in 2018 times the coefficient of sensitivity. (Since countries are not points in space, an alternative would have been to use a GDP-weighted temperature.) Finally, we apply the growth coefficients from the previous footnote to the temperature change and its square induced by global warming using as baseline the average national temperature over the period.

Source: Authors' calculations based on estimates in Burke, Hsiang, and Miguel (2015).

with heatwaves. Adaptations for such damages are likely possible, for example, the installation of air conditioning, especially for the elderly and other sensitive individuals.

Studies like the PESETA in our view provide credible information about the consequences of climate change. The problem is that the list of mechanisms very likely excludes important channels. The PESETA study acknowledges this weakness and notes that potentially important impacts—such as the displacement of people, conflicts and security, and biodiversity—are not quantified and that this list of omissions is likely far from exhaustive.

The PESETA study points to mortality as a key mechanism whereby climate change affects welfare. Tamma Carleton and colleagues (2022) recently published a global study on the mortality effects of climate change, with estimates of costly adaptation based on a revealed preference methodology. They 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

Figure 6 Preadaptation climate damages in the European Union and United Kingdom

Source: European Commission (2020).

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 at 3.2 percent of GDP. This includes both higher mortality and costly adaptation. A striking result of the analysis is the large uncertainty. They provide a 50 percent confidence interval, −5.4 to +9.1 percent of GDP. Equally striking is the large variation across different parts of the world: For Europe and the United States the estimates are 0.1 percent and 1.0 percent, respectively, while for Bangladesh and Pakistan they are 18.5 and 27.5 percent, respectively.

We conclude this section with the following summary observation.

Observation 7. *Credible bottom-up quantifications of the effects of climate change point to fairly small aggregate impacts in the advanced economies. But these studies cannot 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 heterogeneous.*

Taking Stock

Climate science has made impressive advances in understanding of the consequences of emitting CO_2 and other greenhouse gases. The consequences are extremely heterogeneous, but all directly related to the change in the global mean temperature, which, according to scientific 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 CO_2 emissions continue. However, there is a large degree of uncertainty around the strength in this linear relation. Nonlinearities, including global tipping points, cannot be ruled out, especially in the long run. Risks for nonlinear relations at a regional scale and for the probability and intensity of extreme weather events are larger and more acute.

The knowledge of the quantitative aggregate consequences of climate change for human welfare is more limited. Studies point to relatively small aggregate impacts, in particular in the advanced economies and when compared to historic growth rates on a centennial scale. However, many of the effects considered are extremely difficult to convincingly predict. Current climate policies around the world together suggest global warming that, toward the end of the century, makes it physiologically impossible to work outdoors during recurring heatwaves in densely populated areas of India. The impact of such events depends on how rich and technologically advanced India will be by then, something that is hard to predict.

Furthermore, many of the most worrisome consequences of climate change are hardly observable yet in the data. Reduced-form econometric studies therefore can only provide limited information. The consequences and probability 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 Knightian. In our view, this limits the value of cost-benefit analyses aimed at determining an optimal overall emission path or at narrowing a range for the social cost of carbon. Similarly, calculations of an optimal tax on carbon emissions need to be based on assumptions that very likely will remain highly questionable for the foreseeable future. That a policy is optimal for a particular set of assumptions is therefore of limited policy relevance.

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 over time. Furthermore, waiting implies accumulating more CO_2 emissions, which year by year increase global warming and the risk of potentially damaging consequences. Thus, the value of waiting is low and its cost is high. A “wait and see” strategy can thus be dismissed.

Given the large amount of Knightian uncertainty and net cost of waiting, our view is that a robust climate policy should be sought. A robust policy is one that provides acceptable outcomes for a large set of realizations of the for variables about which there is uncertainty. It is therefore a *low regret* policy. We will argue that such a policy requires a significant reduction in global emissions of greenhouse gases, with the aim of reaching net zero of CO_2-emissions well before the end of the century. To support this argument, economic models are 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. Equally important, economic models can be used to quantify the cost of policy mistakes. Given the high uncertainty, policies chosen today will with hindsight very likely turn out to be suboptimal. Calculating the cost of such policy mistakes is a key input in the search for a robust climate policy. We return to this issue after describing our macroeconomic climate model. We end this section with the following tentative conclusion.

Conclusion

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

ii. Calculations of the social costs 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 in climate science and damage measurement.

iii. Given the consensus around both the basic mechanisms and the quantitative uncertainty surrounding them, we consider good climate policy to be a "robust" one that provides acceptable outcomes for a wide set of assumptions rather than being optimal for some particular but uncertain ones.

A Quantitative Global Climate-Economy Model

We now describe a simple integrated assessment model. It is, like Nordhaus's DICE and RICE models, neoclassical in its core, which means that, with proper parameter calibration, it can be made consistent with stylized facts on the historical process of economic growth.[21]

By insisting on matching the key aggregate features of the historical data, we follow the same procedure as do climate modelers.[22] 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 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 eight regions, and we also consider a one-region world. One of the eight 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 reflects scarcity: conventional oil is in limited supply and is costless to extract.[23] This region is calibrated to represent the OPEC members and Russia. The remaining seven regions represent Europe, the United States, China, South America, India, Africa, and Oceania. They all produce a single common final good. There is no international capital market.

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

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

[21] 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.

[22] Our setting is described in detail in Hassler, Krusell, and Olovsson (2021a). The results here come from a recalibrated version of the model where; in particular, we incorporate results from Folini et al. (2024).

[23] 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 a major influence on our results compared to a model where foreign investment of oil incomes is allowed within some limits. Allowing perfect international capital markets would produce highly counterfactual current account balances.

where $A_{i,t}$ is total factor productivity that is exogenous to region *i*. In previous work we have shown that (i) 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; and (ii) 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 (Hassler, Krusell, and Olovsson 2021b). Since the focus here is on the long run, we adopt the Cobb-Douglas specification and merely note that 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. Specifically, we assume that China converges to a balanced growth path with approximately twice the GDP of the European Union and United States, whereas India and Africa both converge to a path with the same GDP as the European Union and United States. The speed of this transition is set so that around 25 percent of the productivity gap is closed each decade.

Energy services are produced competitively with firms using a nested constant elasticity of substitution production function in different energy sources. One region, the United States, has access to nonconventional 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—fracked and conventional oil are very close substitutes. 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 possibly 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 to the representative household in each region. When we introduce carbon taxes, we assume that the tax per unit of carbon grows at the same rate as the GDP trend.

As mentioned above, our model includes 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 consequence other than aligning the production costs of these energy sources.

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

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

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. This functional form 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 preindustrial levels, 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 preindustrial level at time $t-1$ and γ_i is a region-specific climate damage sensitivity.[24] $z_{i,t}$ 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 very easy 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); and
4. the prices for other inputs (e.g., wages and rental rates for capital) are set equal to their marginal products.

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 supply of conventional oil is perfectly inelastic. This since the income and substitution effects of future oil prices cancel each other out in the forward-looking optimal supply decision of the oil-supplying region. 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.[25] Finding the optimal tax is more challenging but, as we argued above, finding the optimal tax for a given set of assumptions is not very policy relevant, given the large Knightian uncertainty. The practical relevance of the present model instead comes from using it to study its positive implications across a larger set of assumptions and policies.

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 per barrel. The production costs for fracking and coal are $40 per barrel and $74 per ton, respectively. Calibrating the cost of using green energy is challenging since this category consists of a large variety of 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.

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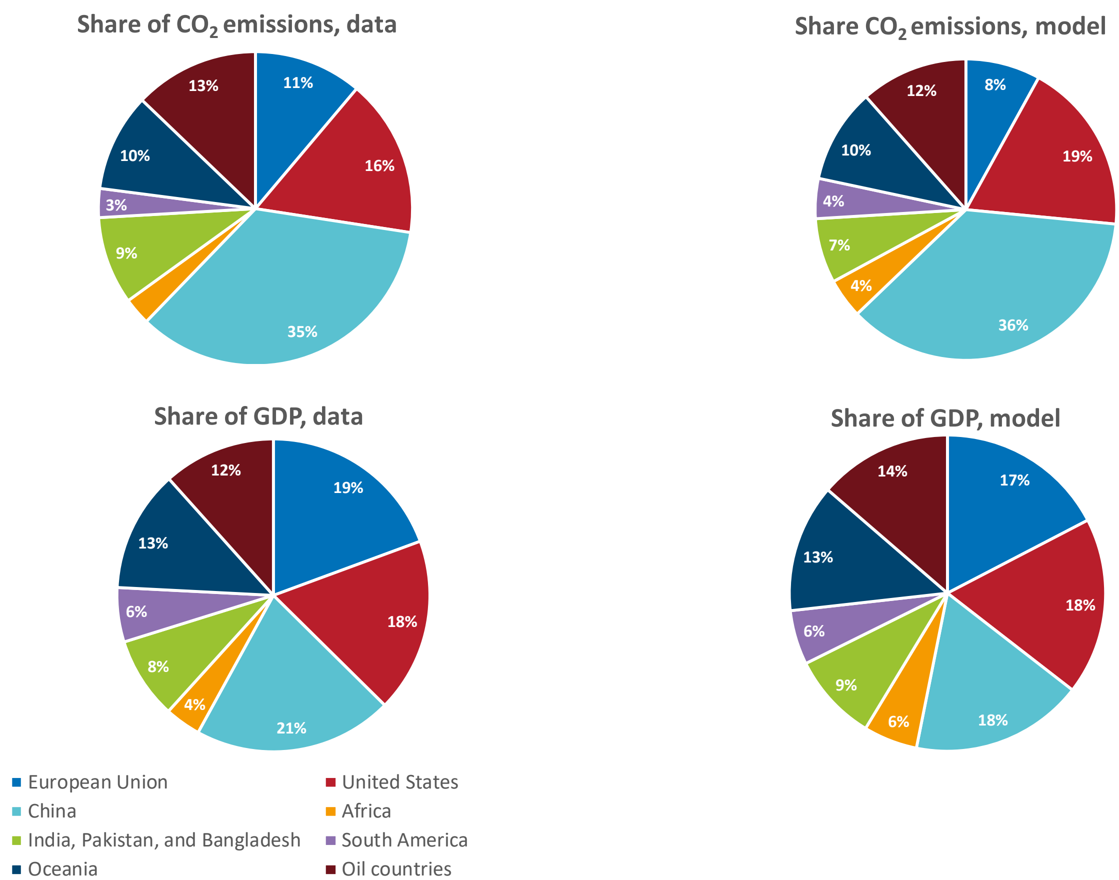
[24] The use of $\tilde{S}_{t-1}$ for period *t* productivity here is more convenient for solving the model numerically than using $\tilde{S}_t$. $\tilde{S}_t$ moves very sluggishly, so the results would barely change if we used $\tilde{S}_t$ instead.

[25] Even Excel can be used in solving the present model, which is not an argument for the model from a scientific perspective but makes it very useful for teaching, including at the undergraduate level.

We calibrate the starting values of the variables in equation (6) so that the distribution of output and CO_2 emissions match the data (figure 7).

Figure 7 Model contributions to global GDP and CO_2 emissions, by region



Source: Hassler, Krusell, and Olovsson (2021a).

Policy, Policy Mistakes, and Their Consequences

We now use the model to study the effects of policy. We analyze several 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.

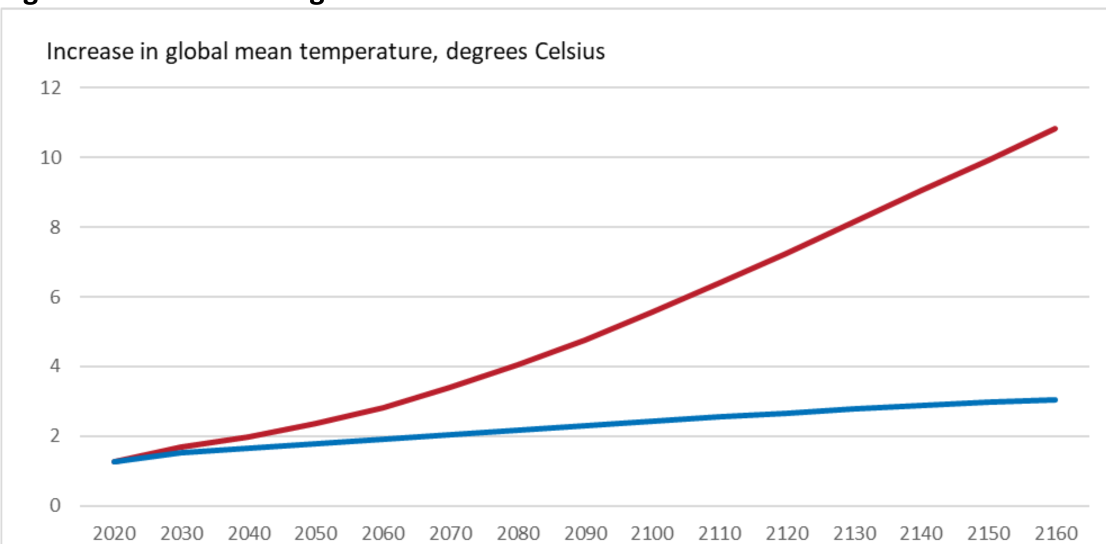
Effects of Different Degrees of Abatement

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 Emissions Trading System (ETS) before the recent reforms of this system. Since the economy is growing, the tax grows at a rate in line with GDP growth.

Without this assumption, the effect of any tax would vanish over time. As noted, we use it in all simulations.

The starting tax rate we use in this experiment is €20 per ton of CO_2. The combustion of a liter of gasoline produces around 2.5 kilos of CO_2 and 1 kWh of coal-powered electricity yields 1 kilo of CO_2, so 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 quite modest tax. However, as shown in figure 8, the tax has a substantial effect on emissions. Comparing figures 8 and 2, we see that the modest tax leads to less global warming than if current emissions are kept constant.

Figure 8 Global warming under business as usual and under a modest emission tax



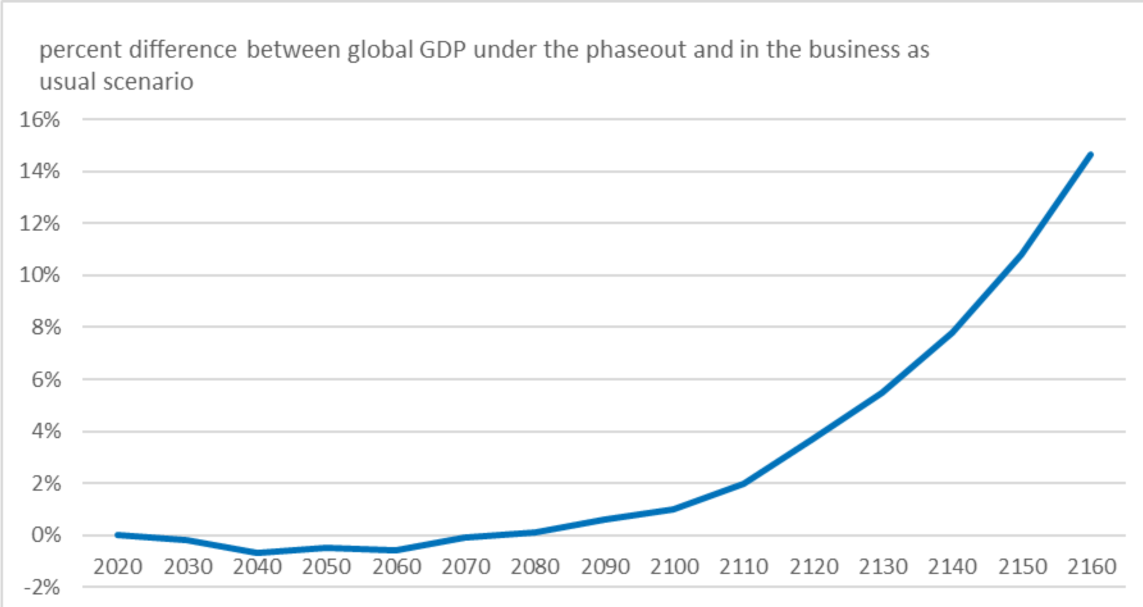
Source: Authors' calculations.

This delivers our first tentative result (we 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 phaseout of fossil fuel, roughly in line with the Paris Agreement. We gradually force emissions down linearly from the current levels of around 40 $GtCO_2$ per year to 4 and assume that these remaining 4 units can be removed by carbon capture and storage (CCS). The gradual reduction is chosen so that the cumulative global emissions are 775 $GtCO_2$. The implied emissions per decade are thus 351, 242, 133, and 47 until carbon neutrality has been achieved. Recall that we assume 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 conventional oil is so high. The implication is that emissions per period are bounded from below by $(1 - \beta)$ times the remaining oil reserves. We use OPEC's estimate of the remaining oil reserves, 1,190 billion barrels, as

Figure 9 Effect on global GDP of a fast phaseout of fossil fuel



Source: Authors' calculations.

representing the amount of conventional (zero extraction cost) oil still in the ground (OPEC 2019). 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 9 shows the difference between global GDP under the phaseout and in the business-as-usual scenario. The key takeaway is that the costs of the phaseout are limited: only around 1 percent of GDP. Later in the century there are gains, but as we discussed above, they are highly sensitive to the climate sensitivity to emissions and the sensitivity of damages to temperature, about both of which there is very limited knowledge at present.

In our 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 percent 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 by then are low—just above 10 percent of current emissions—the carbon tax per unit of emitted CO_2 is quite high. However, recall our argument for allowing 10 percent of current emissions permanently. We assume these emissions can be handled with CCS. If so they 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.

We reemphasize 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 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. The 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. Its estimates imply that the current total investment share of GDP needs to go up by around 2 percentage points by 2030. This is certainly a substantial increase, but it is not historically exceptional. The global investment share in 2010–19 was 24.4 percent, and almost 2 percentage points higher, at 26.1 percent, during the period 1970–99. Nevertheless, the increased investment rate must impact consumption negatively even if GDP is not affected.

Political frictions could also increase costs. Uncertainty about future climate policy 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 lead to local popular resistance. Even if a green transition can have acceptable costs, it could be very costly if designed badly.

We summarize the foregoing in the following tentative result.

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

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 Pigouvian principle) should equal the marginal externality damage costs at all points in time. As noted in our discussion above on the large Knightian uncertainty, we are far from sure of what these optimal tax values are. However, we can still consider departures from the Pigouvian 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.[26]

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 the Nordhaus and Moffat (2017) metastudy on global climate damages to calculate a range of likely climate damage sensitivities. We then define two opposite policy mistakes:

1. **Hoping for the good, but ending up with the bad**. We calculate an optimal tax given a parameterized model, using the formula in Golosov et al. (2014), based on the assumption that the climate sensitivity is at the lower end of the 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. We then use this tax in the model

[26] There is a large literature on formal methods for finding robust policies; here, we illustrate based on our earlier work (Hassler, Krusell, and Olovsson 2018, 2021a).

under the assumption that the assumed sensitivities are instead at the upper ends of their likely intervals. We use our model to calculate the ex post cost of this policy error expressed as a share of GDP (or equivalently as a share of the 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 likely ranges. The truth 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 10 shows the regional costs of the two policy mistakes. In most cases there is a stark asymmetry between the two: It is not very costly to have introduced ambitious climate policy in vain, but the opposite—not having introduced policy when needed—is substantially more costly. 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 significantly increase the cost of policy mistake 1.

The asymmetry is less pronounced for the United States and absent for the first half of the simulation. This is explained by our assumption that the United States has an unlimited supply of fracked oil, which can be used at a cost of $40 per barrel. Under the ambitious climate policy, these reserves are used much less than what is optimal (for both the United States and the world). The assumption of unlimited relatively cheap oil reserves in the United States is largely a matter computational convenience, so this particular model implication is not entirely robust.[27]

Finally, the oil-producing countries lose from taxation in vain, which is in effect a transfer to the oil consuming regions. However, this is comparatively small. The global asymmetry of the costs of the two policy mistakes is very large (figure 11).

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

Policy Errors II: Departing from Global Coverage

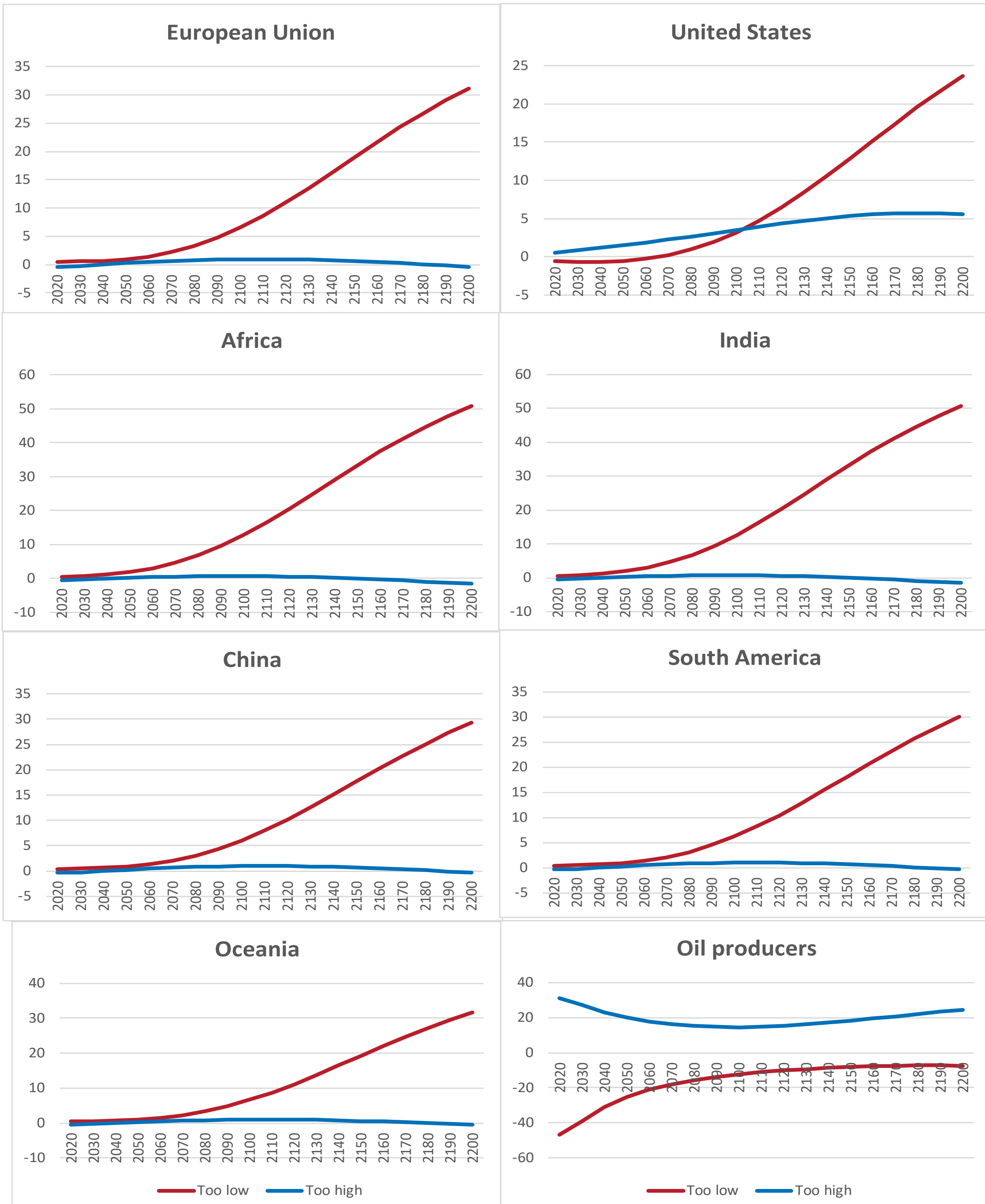
We now turn to global climate policy. Specifically, we ask how costly it would be if some regions do not tax carbon while others compensate with higher carbon taxes. We start with a global climate policy that is moderately ambitious, i.e., based on a relatively low uniform global carbon tax.[28] A climate sensitivity in the middle of the IPCC range would imply global warming at 3.1°C 150 years from now. We select regions for which carbon taxes are set to lower values, while taxes are raised uniformly in the remaining regions to meet the same final temperature increase. We assume that India and Africa do not participate. It turns out that whatever tax

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

[28] Such a carbon tax is calculated as one that would be optimal for intermediate values of the sensitivities discussed above.

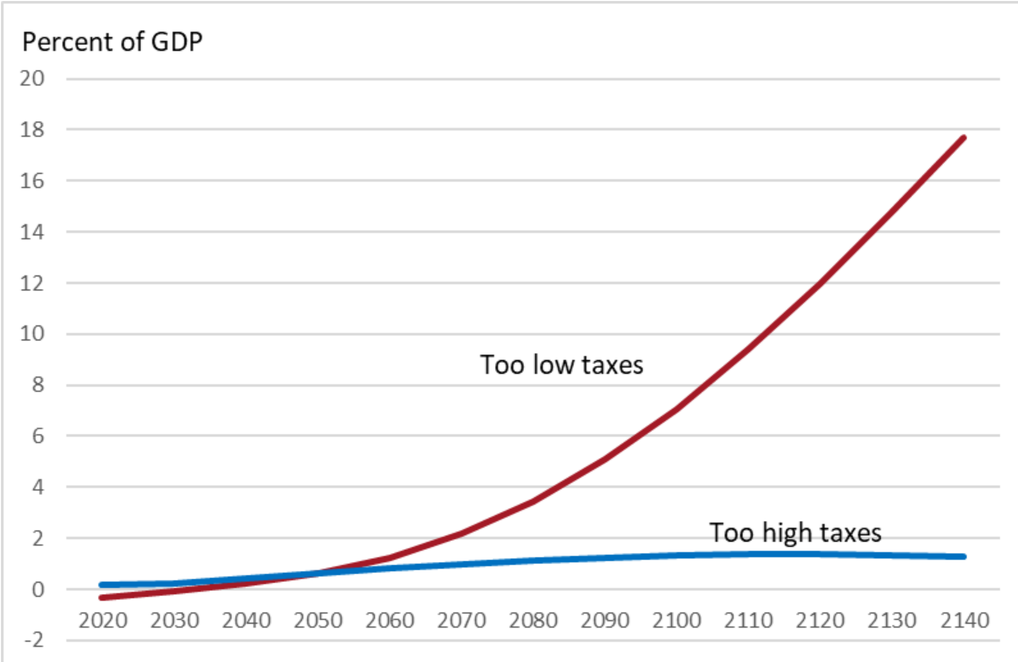
Figure 10 Costs of policy mistakes 1 (too low taxes) and 2 (too high taxes) by region

Percent of GDP



Source: Authors' calculations.

Figure 11 Global costs of policy mistakes 1 (too low taxes) and 2 (too high taxes)



Source: Authors' calculations.

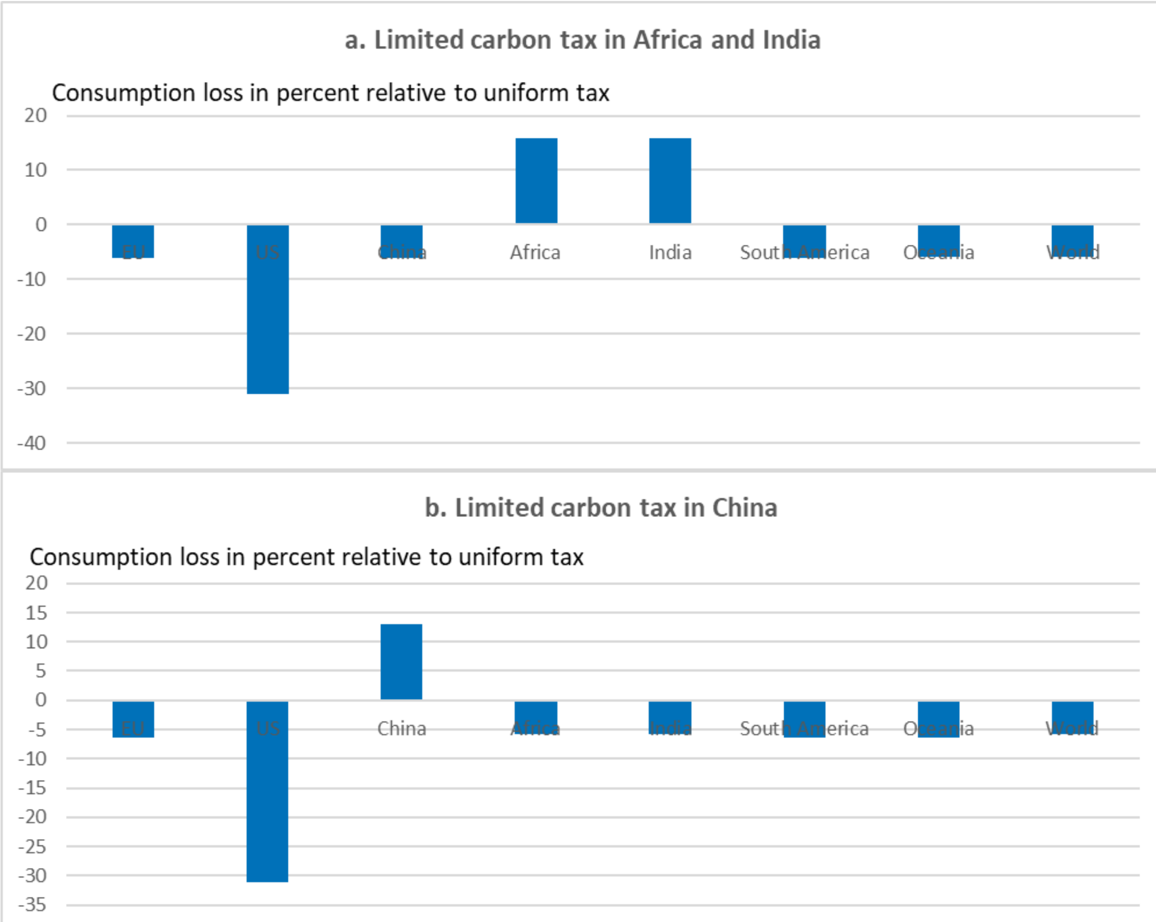
rates is set in the rest of the world, the target will be exceeded. We thus somewhat arbitrarily set the tax in Africa and India to 13 percent of the uniform tax, in which case it is possible to limit warming to 3.1°C. However, the remaining regions then need to implement a tax that is 20 times higher than in the uniform case. The welfare costs in consumption equivalents are shown in the upper panel of figure 12.

We see that India and Africa gain and the other regions lose—indeed, they lose much more than India and Africa gain. Their large losses 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 if China does not participate. We again find that it is impossible to meet the target unless China implements a carbon tax. In order to reach the target, the Chinese tax must be 17 percent of the uniform tax when the remaining regions implement a tax that is 20 times higher than the uniform tax. This is extremely costly in consumption terms (lower panel of figure 12). In our model, we have assumed that only the United States has access to fracking technology; this makes the country more vulnerable to a high carbon tax, explaining its relatively large cost.

The explanation for the cost of nonuniform taxation is that the marginal cost of taxation increases in the tax rate. Clearly, the marginal cost is zero at a tax rate of zero. As we show above, even a low tax rate can be quite effective in reducing emissions (see Hassler, Krusell and Olovsson 2021a for more details on this result, which we consider to be quite robust). This brings us to the following.

Figure 12 Welfare costs of differential global carbon taxation, by region



Source: Authors' calculations.

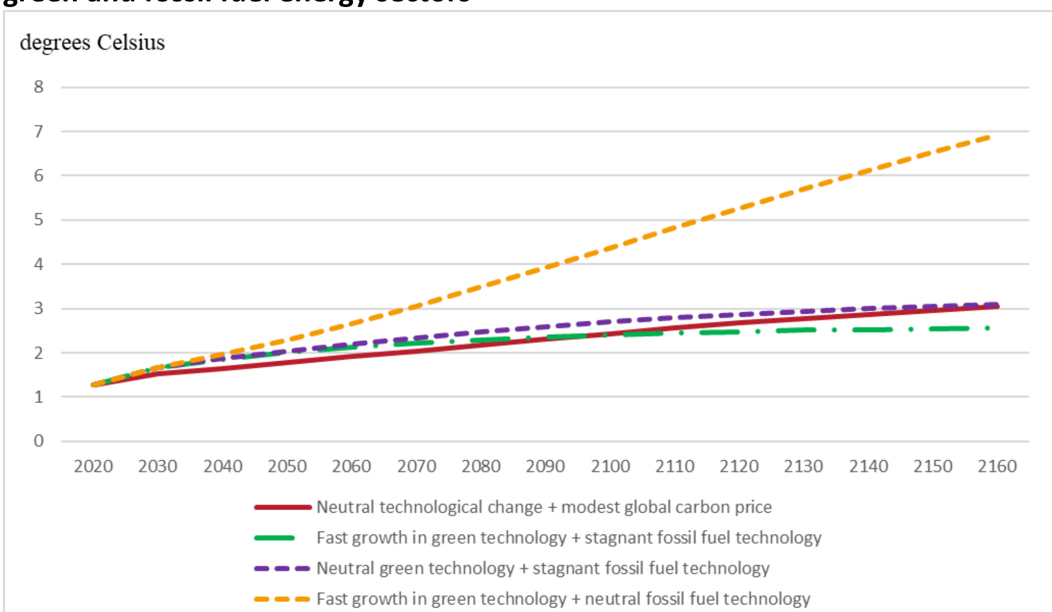
Tentative result 4. *A successful climate policy requires that all regions of the world participate. Compensating for large regions that fail to introduce policies limiting fossil fuel use is very costly, or downright impossible.*

Policy Errors III: Subsidizing Green Technology Instead of Taxing Carbon

In policy discussions, it is sometimes argued that subsidies to green energy, or the development of green alternatives, can 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 about the growth rates of the production costs of elastic energy sources (coal and green). In our benchmark calibration, we assume that the prices of coal and green energy 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. But in reality, green technologies are becoming cheaper fairly quickly, as a result of both market forces and subsidies. We therefore 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 percent per year. We also study the consequences of halting technical change in the coal sector so that its relative price increases by 2 percent per year.

The results for the global economy are depicted in figure 13. As a benchmark, we include the case with neutral technological change and a modest global carbon price (solid red curve). We see that fast growth in green technology, involving falling prices for green energy, is not an effective substitute for carbon pricing (orange dashed curve). In fact, emissions and the global temperature both increase somewhat faster even than in the business-as-usual scenario. On the other hand, stagnant fossil fuel technology, involving relative prices of coal that increase over time (purple dashed curve), turns out to be an effective substitute for carbon pricing both by itself and if combined with faster green growth (green dashed curve). With fast green technology growth, the world uses much more energy, and that is good for growth but has no climate benefits.[29]

Figure 13 Increase in global mean temperature for different technological growth rates in the green and fossil fuel energy sectors



Source: Authors' calculations.

Policy Discussion

In our model, there are no explicit frictions or other market failures than the climate externality, so nothing more than a carbon price is needed. In the real world, in contrast, many other policies are likely to be necessary. Here, economic models are also highly useful. However, due to the multitude of possibly important frictions, we abstain from a formal

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

analysis and instead provide a verbal discussion, a classification and a description of policies implemented in the European Union and the United States.

We believe it is convenient to classify climate policy in three groups, with distinct purposes. We argue that good policies from all three policy groups are critically required.

1. Policy tools 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 (e.g., banning certain technologies) is in principle possible.
2. Tools to overcome economic and political frictions that can make the transition to climate neutrality induced by group 1 policies too costly socially, economically, and/or politically. Examples are subsidies, free allowances, redistribution of various kinds, and industrial policies.
3. Policies to induce other countries/regions to participate in the climate transition.

It should be noted that, although the three policy groups are complementary to achieve the overarching goal of making the world climate neutral, policy evaluation needs to be different across them. Specifically, it is natural to measure the effectiveness of group 1 policies in terms of cost per ton of abated emissions or simply by how much emission reductions are achieved. In group 2, 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 1), policies in group 2 cannot affect emissions since they are determined by the cap. Instead, policy group 2 tools need to be evaluated in terms of how well they reduce frictions and facilitate the development of green alternatives to the fossil fuels phased out by the group 1 tools.

The European Example and the US IRA

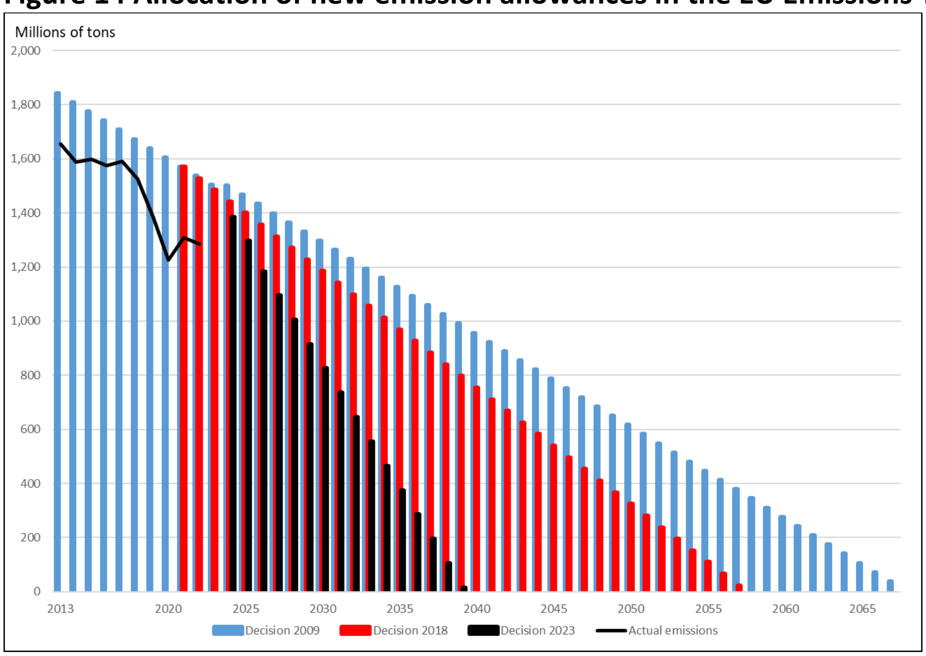
On June 30, 2021, European climate neutrality by 2050 became binding European law. A reduction of emissions by 55 percent compared to 1990 to be reached by 2030 was also included in the European Climate Law. Just before this agreement, the European Commission had presented a plan for how to reach these 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. At the time of this writing, agreements on almost all the elements of the proposal have been reached and they involve a plan very close to the original proposal; only some details remain to be finalized. There are three pillars in the policy package: (1) faster reduction in the number of emission allowances allocated every year in EU ETS 1, (2) a new cap-and-trade system for heating and land transportation (EU ETS 2), and (3) 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 the group 1 policies, i.e., they imply very reasonable limits on emissions of CO_2 in in the European Union for the entire future. To illustrate this point, we describe the package.[30]

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

The first pillar in the package concerns the EU ETS 1, implemented in 2005. This is a cap-and-trade system that now covers about 15,000 firms in heavy industry such as steel and cement production, power, air transportation in the European Union, and from 2024 intra-EU shipping. Within the system, 43 percent of the allowances are distributed free of charge to participating firms and the rest are auctioned out. There is a liquid market for the allowances that can be saved for later use. Firms must each year surrender an allowance for each ton of greenhouse gases they emitted. The system covers close to 50 percent of the union's CO_2 emissions.[31] 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 was increased by reforms in 2009 and 2018. The agreement on the Fit for 55 package almost doubles the yearly reduction relative to the previous rule, 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 14. From 2020 until then, emission allowances corresponding to approximately 17 $GtCO_2$ will have been allocated.[32] This puts a strict limit on emissions for all the covered industries. Steel and cement plants, power producers, airlines, and shipping companies that have not adopted emission-free technologies by 2039 will have to shut down. The Fit for 55 package also includes the gradual phaseout of the distribution of free emission allowances, replaced by auctioning with revenue accrual to the member states.

Figure 14 Allocation of new emission allowances in the EU Emissions Trading System 1



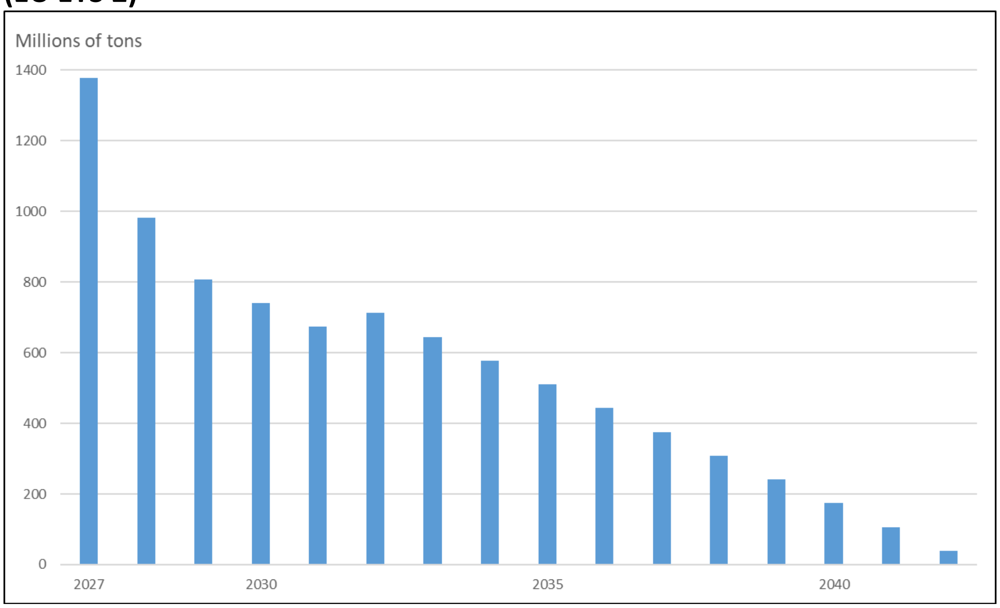
Source: Nilsson (2023).

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

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

The second pillar in the Fit for 55 package 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 noteworthy exception is agriculture which is not covered by either EU ETS 1 or 2. The main greenhouse gases emitted from agriculture is methane and NO_x and it is important to note that cumulative carbon budgets are not relevant for these other greenhouse gases for which it is the flow of emissions that drive climate change, not the cumulative emissions, since they only stay in the atmosphere for a relatively short time. The decentralized and comparatively small-scale production that lead to emission 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 out of the emission trading systems. The EU ETS 2 will start in 2027 and the number of emission allowances auctioned each year will fall, reaching zero in 2042 provided the decided reduction rules are not changed.[33] After 2042, fossil fuels will in principle be forbidden in the union. Under the proposal, around 7 $GtCO_2$ will be emitted under EU ETS 2. The number of yearly allocated emission allowances is depicted in figure 15.

Figure 15 Allocation of new CO_2 emission allowances in the EU Emissions Trading System 2 (EU ETS 2)



Source: Nilsson (2023).

The third pillar is a tightening of 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 grams of 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 overperformance to other manufacturers. After 2035, the sale of new cars that can run on fossil fuel will be prohibited. Compared to carbon taxes, an emission trading system provides exact control over the cumulative amount of emissions. This may have a pedagogical advantage when dealing with

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

CO_2 emissions since it is cumulative emissions that drive climate change and IPCC provides estimates of remaining carbon budgets. The issue of whether a particular carbon tax is high enough to reach a particular emission reduction does not arise if an emission trading system is the policy tool. Another advantage is that by controlling the quantity, there is no spillover risk to global emissions if carbon taxes are not adjusted to changes in demand.[34] A third advantage is that it is arguably easier to politically commit to a particular path of emissions than to a contingent path of taxes that will result in the same emission path.

Because EU ETS 1 and EU ETS 2 will cover almost all CO_2 emissions, it is straightforward to calculate cumulative EU emissions. Given that the decided rules for phasing out the distribution of new emission allowances are kept unchanged, we estimate that approximately 34 $GtCO_2$ will be emitted from 2020 and over the entire future. With 450 million EU citizens, this is 75 tons per capita. If all countries did the same, global accumulated emissions would be 600 $GtCO_2$. This is close to the carbon budget for 1.5°C and far below that for 2°C warming. Thus, the European Union is doing what is required according to the Paris Agreement when it comes to limiting its CO_2 emissions. The Paris Agreement also requires that richer countries take a wider responsibility for the global transition to climate neutrality. But for the European Union to do this by a substantially faster phaseout of emissions would be very expensive for the union and not very helpful for the poorer countries. Other means will be more effective for taking up this responsibility, in particular technological and financial transfers. In conclusion, the Fit or 55 package essentially accomplish what is required under policy group 1.

It remains is to adopt other policies—i.e., those in group 2—to make the transition smooth. Many of these policies at least partially need to be designed to meet specific national challenges. This provides an argument for them to be determined at the national level. Examples are regional policies, energy infrastructure and redistribution. This contrasts to group 1 policies that always should be determined at as high a level as possible.

Finally, policies in group 3 must be developed. This is perhaps the most difficult task and outside the scope of this paper. A successful global transition to climate neutrality requires financial and technological transfers to developing countries and probably clever use of trade policy to strengthen the incentives for all countries to participate. We want to note, however, that our argument that a transition to climate neutrality can be achieved without large sacrifices in terms of growth makes it possible to be optimistic here.

The United States has chosen a different climate strategy with the Inflation Reduction Act of 2022. The backbone of the policy package consists of large subsidies to nonfossil energy production, transmission, and storage, to green infrastructure, and investments in energy efficiency. A key purpose is to increase the supply of nonfossil energy and reduce its price. Our analysis above suggests that subsidies to green energy are not adequate 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 is likely politically impossible in the United States at present, particularly if carbon taxes, or the revenues from an ETS, accrue to the federal government. However, it is possible that the subsidies to green energy will pave the way for

[34] 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).

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 ETS. The optimal speed with which fossil fuels should be phased out differs between different parts of the economy; with an emission trading system or with carbon taxes, the market steers the allocation: it determines where the phaseout will be faster. With direct regulation, this needs to be decided by the regulator.

Going Forward: Research Needed

We have argued that research aiming to derive an optimal carbon tax 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 to 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, making mitigation policy unnecessary. We regard this view as highly hazardous and therefore do not discuss it.)

We instead argue that the macroeconomic focus should be on improving inputs to the policy discussion to answer the *how* question. What would be of great value, in particular, is further insights on how different policies affect the economy, in terms of both 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 overly 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 fuels, is another key issue. In our model, the elasticity of substitution between fossil fuels and green energy sources in production plays this role, together with their respective cost parameters. Related, it would be valuable to have 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 ensure a smooth transition 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 rule out. Global cooperation might also break down, implying a return to something closer to the old business as usual. Because of this, plan Bs should also be developed; they would likely involve large-scale geoengineering (e.g., Fuglesang and Hassler 2023).

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