Climate change economics

Osti, Davide

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CLIMATE CHANGE ECONOMICS[1]

Abstract

I briefy review and comment on some papers about climate change economics through time and space along the following exposition, especially centering on the work of William D. Nordhaus' dynamic integrated climate economy model (DICE) and other integrated assessment models to study the effect of climate change on temperatures, amenities, and the economy more broadly.

"**Dynamic climate clubs: On the effectiveness of incentives in global climate agreements**" by **William Nordhaus**, appeared on **PNAS 2021**, proposes a single period coalition formation model characterized by the emergence of a non - cooperative free - riding equilibrium. The paper studies coalition formation and stability in climate clubs such as the Paris Agreement of 2015, considering a strong abatement structure, as well as an appropriate incentive structure. It takes into account tariff penalties and an international target carbon price based on a cap - and - trade system or carbon taxes. The paper focuses on a supportable policy based on abatement and trade sanctions as well as emission prices or limits; international treaties are treated as clubs composed of the adhering countries; a model is proposed, simple and computable, labeled a trade DICE or TDICE for estimating supportable carbon prices, emissions, and geophysical variables such as concentrations and temperatures. The model is mostly based on the structure of DICE, but adds up equations representing the public - goods character of damages, "club" variables such as trade, the gains from trade, and the costs of trade sanctions. Punishments for non - participation are included.

The results of the estimation of the model are that, even with strong trade sanctions of 10% uniform tariffs for non - participation, emissions are reduced sharply in the club compared to the non - club policy, even though they do not reach the high levels of abatement which are the objective of the international climate clubs. Temperature levels in 2100 surpass the targets of 1.5 or 2°C. This supports the conclusion that the incentives in a climate club are non - sufficient to reach international objectives. Two fundamental parameters in the analysis are the rate of decarbonization and the rate of technological change in the backstop technology. Technological improvements lower the cost of participation in international climate clubs, therefore acting as an incentive of global climate policy. Assuming a rapid rate of decarbonization and a quick decline in the cost of the backstop technology, global emissions in 2050 in the TDICE model are slightly negative, and global temperatures remain in the 2°C limit. While the coupling of a strong climate club and rapid technological change are far from the political and technological realism, they do suggest the existence of a political - economic - technological mechanism for attaining ambitious climate goals.

Public goods create a challenge because they open the gates to free riding, where

[1]**Davide Osti**, May 2025
`dottore commercialista and revisore legale -`
`Via della Zecca 1 - 40121 Bologna - Italy`
`devidosti@gmail.com`

some users may enjoy the benefits without paying; governments solve the public goods problem using their powers of taxation to finance public works, such as public enlightenment and satellites. For private activities, people can join together in clubs, mechanisms that allow to provide goods with public - goods characteristics ("club goods"). A club is a voluntary group gaining mutual benefits from sharing the cost of producing an activity that has club - goods characteristics. The benefits from a successful club are large enough so that the members will pay dues and adhere to club rules in order to gain the benefits from membership. Renewable technologies are suggested for adoption, as well as minimal fossil energy consumption, and direct air capture. The estimate is that the backstop technology is available by mid 21st century at a cost of 500 USD/TCO_2 in 2020 US dollars. The model features exogenous technological chance, prices and market size.

In "**Economics of the disintegration of the Greenland ice sheet**" **William Nordhaus PNAS 2019** presents a reduced form GIS model of economic and geo - physical character for policy analysis, including the social cost of carbon. The model features multiple equilibria with hysteresis in an earth system that changes and shows that social cost - benefit analysis and damage - limiting strategies can be properly adopted to shed light on issues with major long - term consequences, as well as issues such as tipping points, irreversibility, and hysteresis. The study integrates an economic model of climate change with a small structural model of Greenland Ice Sheet (GIS). As such, it provides a way for including large earth system changes into standard economic cost-benefit or damage-limiting analyses. It finds that adding the GIS has only a small effect on the social cost of carbon (SSC) because melting is slow and damages are far in the future. The GIS-stable "base temperature" adopted in the paper is about 0.3 °C above prehistoric temperatures.

The study develops a model of GIS equilibrium and dynamics which is based on current studies but sufficiently compact to integrate fully in an economic model. The result is the DICE-GIS model, that includes the typical components of the DICE-2016R2 integrated assessment model. Based on this combined model, the paper then examines baseline (no-climate-policy) and optimal climate policies along with different constraints, parameters, and discount rates. The study shows that an integrated economic-geophysical modeling is a promising methodology to policy analysis of major earth system changes. While the study applies only to the GIS, the same method can be used for other major and potentially catastrophic changes, such as those pertaining to the Antarctic ice sheet or changes in the North Atlantic thermohaline circulation. Integrated modeling will help inform alternative policies and results as well as the design of global plans to prevent catastrophic changes.

Marine sheet instability is considered as well as multiple locally stable temperature-volume equilibria for the GIS; melt rate per unit of time is taken into account as well as sea level rise within a regional energy-moisture balance model. The dynamic of volume adjustment under different global temperature regimes from calculations in Robinson et al. 2012 is modeled. The simplest relationship is a differential equation in which the volume adjusts as a function of actual and equilibrium temperature and actual volume :

$$\frac{\partial V(t)}{\partial t} = g\big[T(t), T^*(t), V(t)\big]$$

The study focuses on mainly on the completely reversible system, initially assuming that the equilibrium function is linear to simplify the analysis; then the previous equation is estimated from Robinson's formulation using the data on alternative estimates of initial melt rates from different studies. $V^*(t)$ and $T^*(t)$ are equilibrium volumes and temperature, while $V(t)$ and $T(t)$ are actual values.

The DICE models views climate change within the framework of economic growth theory à la Ramsey. The DICE models changes the standard growth model to include climate abatement investments, analogous to the conventional capital investments. The model includes elements from economic growth to emissions to concentration to climate change to damages in a way that attempts to represent simplified best attempts in each area.

The results suggests that the melting of the GIS is substantially irreversible on a relevant societal time scale. The GIS will restore when the temperatures will be reduced, but the growth is so slow that, from a person's perspective, disintegration ought to be considered irreversible.

In "**Can We Control Carbon Dioxide? (From 1975)**", **William Nordhaus AER 2019** considers a number of global environmental problems, mainly relating to the energy sector. In particular, it appears that emissions from carbon dioxide particulate matter and waste heat may lead to significant climatic variations. On these, it seems that carbon dioxide will likely be the first man-made emission to affect climate on a global scale, with a relevant temperature increase by the end of the century. Combustion of fossil fuels causes significant emissions of carbon dioxide into the atmosphere; the emissions slowly spread themselves by natural processes into the oceans, the biosphere, and, very slowly, into fossils. Even though this mechanism is not completely understood, it is clear that the residence time of carbon dioxide in the atmosphere is very long, and that at the moment about one-half of the industrial carbon dioxide remains in the atmosphere. The final distribution of carbon dioxide between the atmosphere and other basins is not known, but estimates of the human-made or industrial carbon dioxide remaining in the atmosphere in the long run range between 10 and 50 percent.

The paper has the goal to study the carbon cycle and analyze its implications for climate stability. Emission equations and diffusion equations are considered as well as a stylized model of the carbon dioxide cycle whereby the author considers the sources (natural and man-made), the emissions, the initial sinks (atmosphere, oceans, biomass), the diffusion in the ultimate sinks (the same as the initial ones), the climatic effects which are distinguished between proximate (on temperature, rainfall, and level of the oceans), and ultimate (on agricultural production, on destruction and creation of useful land and capital, on climatic change and on amenities). The main uncertainties in the carbon cycle are related with the diffusion of the emissions, with their climatic effects, and with the effects on man. The connection between energy and climate and man can be seen as the effect of an uncontrolled development, without taking into account the feedback of carbon dioxide onto climate and man. There are various approaches to deal with this problem, among them, the first is doing nothing, the other three strategies imply efforts of reduction of the emissions of CO_2[2].

Control strategies of carbon dioxide emissions range from reducing emissions such as reducing demand and substitution in supply; negate damages such as mixing into oceans and using other offsetting effects (particulates,, paint, band-aids); cleaning up ex post, such as removing CO_2 from air, or growing trees; and finally doing nothing, leaving nature's way and pray. The main contribution of the paper is to study the diffusion of atmospheric carbon dioxide through emission and diffusion equations for the troposphere, atmosphere, and mixed layer of the oceans, as well as to link this process with limits on carbon dioxide concentrations and with the energy sector. Nordhaus formulates an optimization problem which considers extraction, processing, consumption, emission as variables; resource availability, processing balance equations, consumption balance equations, an emission identity, and a mass diffusion equation as constraints; and the analysis is conducted based on the country of resource, the kind of resource, the grade of resource, as well as the country of consumption, the environmental stratum, the demand category, the step in demand function and the time period.

The results of the analysis are that there are many sources of energy that do not imply the emission of carbon dioxide, namely fusion, fission, solar, wind, or geothermal; only nuclear fission is considered as a real alternative to fossil fuels, but the results would be identical with any other non-fossil fuel. The uncontrolled path indeed leads to significant changes in the level of atmospheric carbon dioxide. According to the predictions of the model, atmospheric concentrations in the uncontrolled path rise by a factor of seven over the entire period (until 2095). This is far above what is deemed as a reasonable doubling of the carbon dioxide concentration. Comparing the estimates with the actual path of emissions and concentrations, there is a remarkable similarity, even though the estimated emissions are 25 percent too low. Another important point is that the optimal path does not differ from the uncontrolled path for the first two periods (centered on 1970 and 1995), and that only in the third period (centered on 2020) do abatement measures become needed.

In the model there are five fuels (oil, natural gas, coal, electricity, and hydrogen) and they are used in four sectors (electricity, industry, residential and transport). The question is how does the composition of fuels changes in the different sectors - being possible that the level of final demand changes in those sectors that are supplied by carbon intensive fuels.

In "**Projections and Uncertainties about Climate Change in an Era of Minimal Climate Policies**", **William Nordhaus 2018** uses an updated DICE model to develop new projections of trends and impacts of different climate policies. It also develops new sets of estimates of uncertainties associated with climate change, comparing them with other climate integrated assessment models. The study shows that significant impact on climate are likely to occur if no adequate policies are put in place, suggesting

[2]and therefore on the consumption of fossil fuels.

that it is hardly likely that nations will achieve the 2°C target even in ambitious policies are adopted internationally. The required carbon price necessary to achieve the target has risen over time.

Climate change is still the central issue in environmental economics as of today; the Paris Agreement on climate change of December 2015 has been ratified, but it is limited to voluntary emissions reductions, and the United States has withdrawn from it going backwards. After the Kyoto Protocol expired in 2012, no binding agreement on emissions reduction is in place. Countries have agreed on the 2°C target increase in temperature but this goal is far from reachable based on the current policies. Most countries indeed act following the business as usual industrial practice, largely ignoring the deep implications of climate change. It is difficult to determine the likely outcome for future climate change and damages in an unregulated world. The study aims at filling this gap by investigating in detail the implication of a world without adequate climate policies; in order to do so, it exploits a recent version of the Dynamic Integrated Climate Economy Model (DICE 2016 R2. In particular it is studied the uncertainty linked to some important parameters.

The aim of the study is reached through the estimation of an updated DICE 2016 model which integrated climate and geophysical variables into a growth framework like the Ramsey model. The update of the DICE is the first after the Fifth Assessment Report of the IPCC. The model considers the cost of living adjustment, optimizing a social welfare function inter-temporally, net output which is gross output reduced by abatement costs and damages, with a production function based on a Cobb-Douglas formulation of capital, labour, and technology. Total output is divided between total consumption and total gross investment. The global output concept is purchasing power parity as measured by the IMF. The growth concept is the weighted growth rate of real GDP of different countries, with the shares being the countries shares of world nominal GDP using current US dollars. Growth in the 1980-2015 period was 2.2 percent per year; growth in the 2015-2050 period is assumed to be 2.1 percent per year, while that to 2100 is projected to be 1.9 percent per year.

Population data and projections through 2100 are based on the United Nations; CO_2 emissions are from Carbon Dioxide Information Analysis Center (CDIAC), and updated from various sources; Non-CO_2 radiative forcings for 2100 and projections to 2100 are from forecasts prepared for the IPCC Fifth Assessment. The abatement cost function is the fraction of output devoted to reducing CO_2 emissions, re-weighted to the abatement cost functions of other IAMs exposed in the modeling uncertainty project by Christensen, Gillingham, and Nordhaus 2018. The abatement cost function is highly convex, reflecting the sharp diminishing returns to reducing emissions. The model postulates the existence of a "backstop technology", namely a technology which produces energy services with zero greenhouse gases emission. It also assumes there are no negative emissions technologies if not after 2150. Additionally a damage function is developed, as well as total CO_2 emissions, namely reduced uncontrolled emissions and exogenous land-use emissions.

There is also a geophysical sector comprising a set of equations for the carbon cycle for three reservoirs, atmosphere, upper oceans and biosphere, and lower oceans. All emissions flow into the atmosphere; the calibration of the carbon cycle is designed in such a way to match long term trends in the retention of carbon dioxide in the atmosphere, up to 4,000 years. Further, radiative forcing is taken into account, mostly from anthropogenic sources. All this is featured in an earth system model with a welfare and a goods discount rate which are differing from each other. The goods discount rate should reflect actual economic outcomes, meaning that the assumptions about model parameters should generate savings rates and rates of return on capital consistent with actual observations.

There are two approaches to estimate uncertainties: one is based on time series, another one on variation in models. The time series approach is grounded on a review of historical data on the global emissions/output ratio, estimating an OLS regression with data from 1960 to 2015, then looking at the forecast error for 2100. Including an AR(1) term in the regression allows the forecast error for 2100 to be 13.5 percent of the logarithm of $\sigma(t)$, namely the level and trend of the global ratio of uncontrolled CO_2 emissions to output. The alternative approach is rooted in the standard deviation of the growth of $\sigma(t)$ in the six MUP models for the uncontrolled run.

The carbon cycle is featured by many parameters, the most important of which is the size of the intermediate reservoir (biosphere and upper level of the oceans). Variations in this parameter have major effects on atmospheric retention over the medium term (a century or more), while the other parameters affects mainly either the very short run or the very long run. Given that IAMs have primitive carbon cycles, Nordhaus examined model comparisons of carbon cycles. A study examined various predictions of 11 earth system models (ESMs) by estimating different emission - driven simulations of concentrations and temperatures projections. These adopted the IPCC high emission scenario (RCP 8.5). When faced by RCP 8.5 CO_2 emissions, models simulate a large diffusion in atmospheric CO_2 concentrations, with 2100 concentrations ranging from 795 and 1,145 parts per million (ppm).

According to the study, differences in CO_2 projections are mainly due to the response of the land carbon cycle, suggesting that the size of the intermediate reservoir is the uncertain parameter to adjust. Despite the ensemble standard deviation is not properly appropriate, it is still a useful benchmark for the purpose of the paper. The final estimates adopts a log - normal distribution for the carbon - cycle parameter.

The damage function was revised in the 2016 version of the DICE model to reflect new findings. The 2013 version relied on estimates of monetized damages from the Tol 2009 survey, but it has since been shown that the Tol survey contained various numerical errors. In this paper the damage function was estimated with a method established by Nordhaus and Moffat 2017 that is a survey on damage estimates, turning up 27 studies with 36 damage estimates.

In **"A Survey of Global Impacts of Climate Change: Replication, Survey Methods, and a Statistical Analysis"**, William Nordhaus and Andrew Moffat 2017 formulate a systematic research synthesis of economic models predicting climate change. They refer to the Tol 2009 survey and the the Fifth Assessment Report of the IPCC, focusing on empirical damage functions in integrated assessment models. They adopt a median quadratic weighted regression to study a the sharp convexity in the damage function; the authors advocate a way to estimate the social cost of carbon that disaggregates market and non-market climate damages by regions and sectors, with results presented in both monetary and natural units, and that are consistent with empirical and structural economic studies of sectoral impacts and damages; that include representation of relevant interactions and spillovers among regions and sectors; that recognizes and considers damages affecting welfare either directly or through changes in consumption and capital stocks; that includes a representation of adaptation to climate change and the cost of adaptation; and finally that includes representation of non-gradual damages.

The study adopts a systematic research synthesis based on a meta analysis and a sampling procedure on a number of studies on climate change and economics. The platforms assessed include EconLit, JSTOR, and Google Scholar, the last one being much more inclusive, even though without a well defined set of criteria. EconLit is the only search engine which is used to select relevant contributions to be considered in the survey, based on the abstracts of each study, thus determining their relevance. 24 studies were considered in the end of the search, of which 11 provided sufficient information to quantify global damages. The systematic research synthesis approach was combined with a non systematic research synthesis, combining both formal and informal methods. Some of the studies included involved some estimates of health and ecosystem damages, along with national GDP and per capita GDP figures from the IMF, scaling them appropriately to account for future damages, with a regional disaggregation.

A statistical analysis was performed, considering the individual studies as "data", an approach which is clearly warranted for a standard mèta - analysis, such as in the case of studies reporting independent clinical trials. Nonetheless, some of the studies in the sample are inter-dependent, thus, somehow, not all of them were considered independent data points. Moreover, it has been assumed that there is a true relationship, and that the data points are drawn from that relationship, with errors of measurements of the damages, but not of the temperature changes themselves. The authors began with 36 usable estimates from 27 studies. Then, a set of weights for each study was determined, from 0 to 1, with a weight of 1 being attributed to the latest versions of the estimates that used independent methods, which are deemed appropriate for estimating damages. The criteria for assignment of a high weight are that earlier versions of estimates, studies primarily relying on other studies, and studies using so called uninformative methods provide little information about long - run impacts of climate change, therefore receiving a low weight.

Afterwards, the authors performed a variety of specifications of damage functions: regression specifications (OLS and quantile regressions); alternative versions of polynomial (quadratic term only, linear and quadratic terms, and non-linear with estimated exponent); omitting outliers from the top and bottom, for example omitting estimates with temperature greater than 8°C because they are highly speculative and would have great weight in an OLS regression. Also estimates with temperature less than 2°C are omitted because of their relative unimportance for damage functions in the range of 3 to 6°C, which is most important for the end of the 21st century. The authors' preferred regression is the median quadratic weighted regression, with an impact of -1.63(+/-1.77)%

of income at 3°C warming and -6.53(+/-1.95)% of income at 6°C warming. The errors reported represent forecast errors in the preferred equation. Including all specifications, the impact is -1.8(+/-0.74)% of income at 3°C warming and -6.7(+/-3.0)% of income at 6°C warming. It is noticeable that the weighted regressions yield larger negative predictions (damages) than the unweighted regressions.

An adjustment is made to cover unquantified sectors, described in Nordhaus and Sztorc 2013, with which the estimated impact is -2.04(+/-2.21)% of income at 3°C warming and -8.16(+/-2.43)% of income at 6°C warming. A final relevant finding is the one about the possibility of threshold effects in damages. This relates to the degree of convexity of the damage function. Many damage functions are assumed to be linear-quadratic (as in many versions of the DICE model); by contrast, some researchers believe this damage function is more convex. For example, a sharp threshold has been considered in policy discussions at a temperature increase of 2°C, implicitly implying a very sharp kink in the curve near that threshold.

Various versions of exponential equations have been considered, reporting results of an equation of the type $D/Y = \alpha T^{\beta} + \gamma$, with four versions of it: weighted and unweighted combined with one with and without the linear term (γ); the estimates strongly reject damage estimates with a sharp discontinuity or convexity; instead it appears that the quadratic or linear-quadratic specification is a reasonable way of approximating the results of the damage studies.

To conclude, this study compiles global aggregate damage estimates from climate change, both evaluating the results from Tol 2009, 2014, and carefully documenting a new systematic research summary methodology and making it readily available. Further studies can work towards constructing a general agreement of the literature by performing research syntheses that are both comprehensive and objective. Additionally, this study examines alternative specifications and estimates that can be used for empirical damage functions in integrated assessment models (IAMs). The approach was to use 36 estimates and treat them as data drawn from an underlying damage function. Weights have also been attached to each estimate reflecting the authors' judgment as to whether it contributed to independent information about damages. With the preferred regression of the median, quadratic weighted regression, and with judgmental adjustment of 25% on top of the quantified estimates, the estimated impact is -2.04(+/-2.21)% of income at 3°C warming and -8.16(+/-2.43)% of income at 6°C warming. Another major conclusion is on the likelihood of threshold or sharp convexity in the damage function. A multiplicity of tests suggests that there is no indication from existing damage estimates of a sharp discontinuity or high convexity. Instead, it appears that the quadratic or linear-quadratic is a reasonable approximation of the shape of the damage function.

Finally the impact of estimates covers key sectors such as agriculture, sea-level rise, energy, and forestry. Most do not include many non-market impacts, and the quantification of non-market impacts that do exist are generally just guesses. This suggests that the figures examined in this paper are likely to be underestimates of true damages. The work on impacts is also limited because there are hundreds, perhaps thousands of studies on impacts on different areas such as health, agriculture, energy, and coastal structures. Despite that, few are comprehensive in terms of regions and sectors. Few organizations have the resources ti integrate different studies to prepare the comprehensive estimates that are needed for use in economic-climate modeling. The work on impacts has been performed by a small group of scholars - comprehensive impact studies are an afterthought in the study of climate change, yet they are critical in estimates of policy instruments, such as the social cost of carbon, or the appropriate emissions, concentrations, or temperature targets.

In **Modeling Uncertainty in Climate Change: A Multi Model Comparison**, Gillingham, Nordhaus, Anthoff et al. 2015 discuss about the uncertainties complicating both the analysis and development of climate policy. The NBER working paper illustrates the first comprehensive study of uncertainty in climate change using multiple integrated assessment models. The study focuses on model and parametric uncertainties for population, total factor productivity, and climate sensitivity. It estimates the pdfs of key output variables, such as CO_2 concentrations, temperature, damages, and the social cost of carbon (SCC). The key finding is that parametric uncertainty is more important than uncertainty in model structure.

1. Introduction. The uncertainties in the economics of climate change range from those regarding economic and population growth, emission intensities and new technologies, to the carbon cycle, climate response, and damages, and cascade to the costs and benefits of different policy objectives. The six IAMs analyzed in the paper are representative of the models used in the IPCC Fifth Assessment Report (IPCC 2014) and in the US Government Interagency Working Group Report on the Social Cost of Carbon (US Interagency Working Group 2013). The approach adopted in the paper is a two-track methodology that allows reliable estimate of uncertainty for models of different size and complexity; the first track involves running the models over a set of grid points and fitting a surface response function to the model results; the second step develops probability density functions for the chose input parameters (i.e. the parameters' pdfs) with the best available evidence. Both tracks are then combined using Monte Carlo simulations with the parameter pdfs and the surface response functions.

This methodology allows to provide a clear approach to dealing with uncertainty across multiple parameters and models, and is easily applicable to additional models and uncertain parameters. A positive aspect of this methodology is its replicability; the data from the calibration exercises are relatively compact and are collected in a compatible format, the surface responses can be estimated independently, and the Monte Carlo simulation are easily replicable in multiple existing software packages.

Uncertainties are central in estimating the effects of climate change, and should be communicated clearly and coherently. The focus on uncertainties has become effectively urgent because of the great attention given by scientists to tipping elements in the earth system. Example of tipping elements include the large ice sheets, large-scale ocean circulation, and tropical rain forests. Some climatologists have argued that beyond 2°C global warming will lead to an irreversible melting of the Greenland ice sheet (Robinson et al. 2012). Once uncertainties are considered, policies will need to account for the risk that paths may lead across tipping points, especially those that are irreversible.

An additional issue is that of the likely fat tails in the distribution of parameters, of outcomes, and of the risk of catastrophic events. A fat-tailed distribution is one in which the probability of extreme events declines slowly, so the tail of the distribution is thick; this happens, for example, in the Pareto distribution. As Martin Weitzman showed in a series of papers, the combination of fat tails, unlimited exposure, and high risk aversion implies that the expected loss from certain risks such as climate change is unbounded and we thus cannot apply standard optimization calculations or cost-benefit analyses.

2.a Content. This projects aims to estimate the uncertainties of key model outcomes induced by uncertainty in important parameters. The authors hope to learn the degree of precision to which there is precision in the point estimates of major variables used in major integrated assessment models. How do major parameters uncertainties affect the distribution of likely outcomes of major variables; and what is the level of uncertainty of major outcome variables? This is a question of "classical statistical forecast uncertainty", based on the relationship between emissions, concentrations, temperature increase, and damages in a baseline projection model.

There are various uncertainties revolving around climate change: 1. parametric uncertainty, such as uncertainty about climate sensitivity or output growth; 2. model or specification uncertainty, such as the specification of the aggregate production functions; 3. measurement error, such as the level and trend of global temperatures; 4. algorithmic errors, such as those that find an incorrect solution to a model; 5. random error in structural equations, such as those due to weather shocks; 6. coding errors in writing the program for the model; and 7. scientific uncertainty or error, such as when a model contains an erroneous theory. This study focuses mainly on the first of these, parametric uncertainty, and to a limited extent, to the second, model uncertainty. -the approach involves the application of the principles of judgmental or subjective probability, or "degree uncertainty", to measuring future uncertainties. This approach has roots in the work of Ramsey 1931, De Finetti 1937, and Savage 1954, and assumes that the probabilities are akin to the odds that informed scientists would take when evaluating the outcomes of an uncertain event.

The method relies on two potential approaches, one based on a Monte Carlo simulation where the chosen uncertain parameters are drawn from a joint pdf; the other based on the distinction between the model calibration runs and the generation of the parameters pdfs and the Monte Carlo estimates. The first track adopts model runs from six participating economic climate change integrated assessment models to develop surface response functions; the second track develops probability density functions defining the uncertainty for each analyzed uncertain input parameter. The two tracks are combined through a Monte Carlo simulation to characterize statistical uncertainty in the output variables.

The model is a mapping from exogenous and policy variables and parameters to endogenous outcomes. The model can be written as follows:

$$Y^m = H^m(z, \alpha, u) \tag{1}$$

where Y^m is a vector of model outputs for model m; z is a vector of exogenous and policy variables; α is a vector of model parameters; u is a vector of uncertain parameters to be investigated; and H^m represents the model structure. The models have different structures, model parameters, and choice of input variables; however we can represent the arguments of H without reference to models by assuming some are omitted.

The first step is to select the uncertain parameters for analysis. Once they are selected, each model then does selected calibration runs. The calibration runs take as a central set of parameters the base or reference case for each of the models. It then makes various runs adding or subtracting specified increments for each of the base values of the uncertain parameters. This gives a set of inputs and outputs for each model.

2.b The climate models. The challenge for policies for global warming is particularly difficult because it spans many disciplines and parts of society, such as geophysical, economic and political disciplines - therefore the task of integrated assessment models is pull together the different aspects of a problem, so that projections, analyses, and decisions can consider simultaneously all important endogenous variables. These IAMs aspire to have, at a first degree of approximation, models that operate all the modules simultaneously and with reasonable accuracy.

The DICE (Dynamic Integrated Climate Economy model) was first developed around 1990 and has gone through several extensions and revisions; it was developed by William Nordhaus, and one of the latest editions is the one of 2014, then reviewed in 2023. The DICE model is a globally aggregated model that views the economics of climate change from the perspective of neo-classical economic growth theory; economies make investment in capital and in emission reductions, reducing consumption today, so to lower climate damages and raise consumption in the future. The special feature of the model is to include all the major elements in a highly aggregated fashion; the model is made up of around 25 dynamic equations and identities, including those for global output, CO_2 emissions and concentrations, global mean temperature, and damages. The version for this project runs for 60 five-year periods; it can be run in either an Excel version, or in the preferred GAMS version. The version used here is the one of 2013. The runs were performed by William Nordhaus and Paul Sztorc.

The FUND model (Climate Framework for Uncertainty, Negotiation, and Distribution) was developed mainly to assess the impact of climate policies in an integrated framework. It is as recursive model taking exogenous scenarios of major economic variables as inputs and then perturbs them with estimates of the cost of climate policy and the impacts of climate change. The model has 16 regions and contains explicit representation of five green-house gases. Climate change impacts are monetized and include agriculture, forestry, sea-level rise, health impacts, energy consumption, water resources, unmanaged ecosystems, and storm impacts. Each impact sector has a different functional form and is computed separately for each of the 16 regions. The model runs from 1950 to 3000 in time steps of 1 year. The source code, data, and a technical description of the model are public, and the model has been used by other modeling groups. The FUND was originally created by Richard Tol 1997, and now is jointly developed by David Anthoff and Richard Tol.

The GCAM (Global Change Assessment Model) is a global integrated assessment model of energy, economy, land-use, and climate. GCAM is a long-term global model based on Edmonds and Reilly 1983. The model integrated representations of the global economy, energy systems, agriculture and land use, representing terrestrial and ocean carbon-cycles, and some coupled gas-cycle and climate models. The climate and physical atmosphere in GCAM is based on the Model for the Assessment of Greenhouse-Gas Induced Climate Change (MAGICC), Meinhausen et al. 2011. The global economy is formed by by 14 geopolitical regions, clearly linked through international trade in energy commodities, agricultural and forest products, and other goods such as emission permits. The scale of economic activity is driven, in each region, by population size, age, and gender, as well as labour productivity. The model is solved in a dynamic - recursive fashion for set of market-clearing equilibrium prices in all energy and agricultural good markets every 5 years over 2005 - 2095. The full documentation is open source and developed by the Joint Global Change Research Institute.

The MERGE model (Model for Evaluating Regional and Global Effects of greenhouse gases reduction policies) is an integrated assessment model featuring global energy-economy -climate interactions with regional detail. It was introduced by Manne et al. 1999, and had been continually developed since then; MERGE is a formulation as a multi-region dynamic general equilibrium model with a process model of the energy system, and a reduced-form representation of the climate. It is solved in GAMS through sequential joint non-linear optimization with Negishi weights to equalize inter-regional trade flows. The economy is structured as a Ramsey model where electric and non-electric energy inputs are traded off against capital and labour, and production is allocated between consumption and investment. The energy system has explicit technologies for electricity generation and non-electric energy supply, with a resource extraction model for fossil fuels and uranium. The climate model comprises a five-box carbon cycle and follows all major non-CO_2 greenhouse gases and non-CO_2 forcing agents explicitly. Temperature changes as a two-box lag process, where uncertainty about climate sensitivity is evaluated jointly with uncertainty about the response time and aerosol forcing. The model features 10 regions and runs through 2100.

The MIT-IGSM (Integrated Global Systems Model) was developed in the early 1990s and has been regularly updated. It contains a general circulation model of the atmosphere and its interactions with the oceans, atmospheric chemistry, terrestrial vegetation, and the land surface. Its economic part represents the economy and anthropogenic emissions. The full IGSM was described in Sokolov et al. 2009. The economic component described here is presented in Chen et al. 2015. The earth system component is a simplified general circulation model resolved in 46 latitude bands and 11 vertical layers in the atmosphere, with an 11 layer ocean model. The land system comprises 17 vegetation types. The economic component is a multi-sector, multi-region applied general equilibrium model, and empirical application coherent with neoclassical economic theory. The model operates recursively, where the economy drives the earth system model, but without feedback of climate impacts on the economic system. The economic component is solved for 5 year time steps in GAMS, and here was run through 2100. The simulations for this exercise were run by Henry Chen, Andrei Sokolov, and John Reilly.

The WITCH model (World Induced Technical Change Hybrid) was developed in 2006 by Valentina Bosetti et al.; the latest version included in the paper is fully described in Bosetti et al. 2014. The model separates the world into 13 major regions; the economy of each region is described by a Ramsey type neoclassical optimal growth model, where forward looking central planners optimize the present discounted value of utility in each region. These optimizations consider other regions' inter-temporal strategies; the optimal investment strategy features a detailed consideration of energy sector investments in power generation technologies and innovation, and the direct use of fuels, as well as abatement of other gases and land-use emissions. GHG emissions and concentrations are then used as inputs in a climate model of low complexity. The version used here runs for 30 five-year periods and includes 35 state variables for each of the 13 regions, running on GAMS. The runs were performed by Valentina Bosetti and Giacomo Marangoni.

2.c Key issues. One of the key decisions of the paper was to choose the uncertain parameters; each parameter must be important for defining uncertainty; parameters should be varied in each model without excessive burden, and without violating the idea of the model structure; finally they should be represented by probability distributions, either based on prior research, or feasible within the aim of the project. The uncertain parameters were chosen to be (1) the growth rate of productivity[3]; (2) the growth rate of population[4]; and (3) the equilibrium climate sensitivity (equilibrium change in global mean surface temperature from doubling of atmospheric CO_2 concentrations)[5]. Moreover, two alternative policy scenarios were introduced: one was a "base" run where no climate policies were introduced; and a second in which a rapidly increasing carbon tax was introduced. The modelers tried to introduce uncertainties in technology, but it proved impossible to find one that was both sufficiently inclusive and could be integrated in the models.

Uncertainties about climate damages were excluded because half of the models did not contain damages; a final chance was to consider policy runs that had quantitative limits rather than carbon prices. This approach was rejected because the carbon tax proved simpler to define and apply.

Firstly, the modelers developed a small number of calibration runs including a full set of outputs for a three-dimensional grid of values of the uncertain parameters; for each

[3]The original design has been to include a variable representing the uncertainty on the overall technological change of the global economy; the results of the initial trials showed that the specifications of technological change differed greatly across models, and it was unfeasible to define a comparable technological variable applying to all models.

[4]A uniform change in the growth rate of each region; the uncertainty was specified as a plus or minus a uniform percentage growth rate each year over the period 2010 - 2100.

[5]The major problem was that adjusting the equilibrium climate sensitivity generally required adjusting other parameters in the model defining the speed of adjustment to the equilibrium; the adjustment speed is sometimes represented by the transient climate sensitivity.

of the uncertain parameters, they selected five values centered on the model's baseline values. Thus, for 3 uncertain parameters, there were 125 runs each for the Base and the Carbon Tax policy scenarios. On the basis of the calibration runs, the subsequent step implied estimating surface-response functions (SRFs) where the model outcomes are estimated as functions of the uncertain parameters. The idea was that, if the SRFs could approximate the models properly, then they could be adopted to simulate the probability distributions of the outcome variables properly.

To develop probability density functions, for each uncertain parameter, earlier studies have been explored to determine the calibration. For **population growth**, only one research group made long-term global projections of uncertainty for several years, namely the population group at the International Institute of Applied Systems Analysis (IIASA) in Austria, under the direction of Wolfgang Lutz. The IIASA stochastic projections were developed in the range of a period of more than a decade and are amply used by demographers. The methodology is based on the results of discussions of a group of experts on fertility, mortality, and migration, adopted for producing scenarios of these vital rates of interest.

The forecasts are based on 13 world regions. The forecasts are distributions of the results of 2,000 different cohort component projections. For these stochastic simulations, the fertility, mortality, and migration patterns implied by the individual projection runs were randomly derived from the described uncertainty distribution for fertility, mortality, and migration in the various world regions (Lutz, Sanderson, and Scherbov 2008). The IIASA methodology is based on a survey of expert demographers on subjective probability distributions against individual bias.

The modelers selected the uncertainty revolving around population growth around the period 2010-2100 as the single parameter of interest. They fitted the growth-rate quantiles from the IIASA projections to various distributions, with normal, log-normal, and gamma being the most satisfactory. The normal distribution performed better than any of the others on five of the six quantitative tests of fit for distributions. Based on that, it has been recommended the normal distribution as the reference for the pdf of population growth over the period.

In addition, the modelers developed further additional tests, the first involved the projection errors that would have been generated using historical data; the second looked at the standard deviation of 100-year growth rates of population for the last millennium; and the third examined projections from a report on the National Research Council. While these tests all gave slightly different results in terms of uncertainty ranges, they were similar to the uncertainties estimated in the IIASA study.

As an end of these tests, the authors decided to adopt a normal distribution for the growth rate of population based on the IIASA study with a standard deviation of the average annual growth rate of 0.22 percentage points per year over the period 2010-2100, which is the horizon considered in the study.

The **climate sensitivity** is defined as the equilibrium or long run response in the global mean surface temperature to a doubling of atmospheric carbon dioxide. Referring to climate models, this is calculated as the increase in average surface temperature with a doubled CO_2 concentration relative to a path with the pre-industrial CO_2 concentration.

This parameter also plays a key role in the geophysical components in the IAMs adopted in the study.

Given the importance of equilibrium climate sensitivity in climate science, there is ample literature estimating probability density functions. These pdfs are usually based on climate models, the instrumental records over the past century, paleoclimatic data such as estimated temperature and radiative forcings over ice-age intervals, and the results of volcanic eruptions. The focus is on studies drawing upon multiple lines of evidence. the IPCC Fifth Assessment report (AR5) surveyed the literature quantifying uncertainty in the equilibrium climate sensitivity and evidenced five recent articles using multiple lines of evidence (IPCC 2014). Each paper uses a Bayesian approach to update a prior distribution based on previous evidence to calculate the posterior probability density function. The various studies included in the analysis, each of them was considered as independent from each other, combing them simply.

The primary study included is Olsen et al. 2012, being representative of the literature in using a Bayesian method, with a prior based on previous studies and a likelihood based on observational data, such as global surface temperatures or global total heat content. The prior in Olsen et al. 2012 is mainly based on Knutti and Hegerl 2008. That prior is coupled with output variables from the University of Victoria ESCM climate model (Weaver et al. 2001) to determine the final posterior distribution. The study of Olsen et al. 2012 was chosen because it was recommended by a set of climate scientists, it was representative of the other four studies considered, and sensitivity analyses of the effect on aggregate uncertainty of changing the standard deviation of the Olsen et al. 2012 results found that the sensitivity was small.

To find the estimated pdf from Olsen et al. 2012, a set of equilibrium temperature values and corresponding probabilities was considered; further families of distributions best approximating the numerical pdf provided were explored; finally, a log-normal distribution was chosen to best fit the posterior distributions.

To find the parameters of the fitted log-normal pdf, they minimized the sum of the vertical difference between the posterior pdf and the log-normal pdf over all grid points values in the Olsen et al. 2012 distribution. The fit is very close, with the log-normal distribution always without 0.14% of the Olsen et al. 2012 pdf for any grid point value.

Uncertainty in the **growth of productivity** is deemed to be a critical parameter in determining all elements of climate change, from emissions to temperature change to damages. Climate models generally draw their conclusions on emissions trajectories from background models of economic growth such as scenarios of the IPCC.

Forecasts of long-run productivity growth imply wide debates on topics like the role of new technologies and inventions, potential increases in the research intensity and educational attainment in emerging economies, and institutional reforms and political stability. Despite the empirical literature providence evidence for a variety of models, not enough information to derive a probability distribution for long-run growth rates.

A useful background for estimating trends is made by historical records. Despite that, the authors selected a survey of experts on economic growth to determine both the central tendency and the uncertainty about long-run growth trends. The study exploited information drawn from a panel of experts for the periods 2010-2050 and 2010-

2100. Growth is defined as the average annual rate of real per capita GDP, measured in PPP terms.

Most experts' estimates can be approximated by a normal distribution, with a mean growth rate of 2.29% per year and a standard deviation of of the growth rate of 1.15% per year over the period 2010-2100. The mean growth rate of per capita GDP in the base run of the six models is a little lower, at 1.9% per year over this period. They tested different ways of combining experts responses, finding little sensitivity to the choice of the aggregation method.

3. Results. To help visualize the results, the authors developed lattice diagrams to show the way results change across uncertain variables and models. Figure 3 shows a lattice diagram for the increase in global mean surface temperature in 2100. The y-axis is the global mean surface temperature increase in 2100 relative to 1900; the x-axis is the value of the equilibrium temperature sensitivity. Across the panels on the horizontal axis, the first column exploits the grid value of the first of the five population scenarios (the lowest growth rate); the middle column shows the results for the modelers' baseline population; and the third column presents the results for the population associated with the highest population grid (or highest growth rate).

Going down panels on the vertical axis, the first row shows the highest growth rate for TFP; the middle row shows TFP growth rate for the modelers' baseline; and the bottom row shows the results for the slowest grid point for the growth rate of TFP. The bottom row shows results for the temperature sensitivity parameters.

Another relevant relationship to examine is how the various models react to carbon prices; figure 4 shows the percentage reduction in CO_2 emissions in the Carbon Tax scenario vs the Base run; the x-axis shows the magnitude of the carbon tax; in all models, attaining zero emissions would require very high carbon prices.

To analyze the results of the surface response functions, a linear quadratic interactons specification approach was preferred. The specification is

$$Y = \alpha_0 + \sum_{i=1}^{3} \beta_i u_i + \sum_{j=1}^{3} \sum_{i=1}^{j} \gamma_{ij} u_i u_j \tag{2}$$

here, u_i and u_j are the uncertain parameters. The Y are the outcome variables for different models and different years (e.g. temperature for the DICE model for 2100 in the Base run for different values of the 3 uncertain parameters). The parameters α_0, β_i, and γ_{ij} are the estimates from the SFR regression equations. The subscripts for the model, year, policy, and variable are suppressed.

The linear parameters are the coefficients on the linear term in the SRF regressions; the data are decentered, thus the linear terms in the higher-order polynomials are the derivatives or linear terms at the median values of the uncertain parameters.

The regressions are fit as deviations from the central case, thus coefficients are linearized at the central point, the modelers' baseline set of parameters. Considering the LQI coefficients for temperature, the effects of the equilibrium climate sensitivity on 2100 temperatures varies significantly among the models.

For TFP, the effects are quite similar apart from the WITCH model, which is much lower. For population, the linear quadratic interaction terms coefficients vary by a factor of three.

Four different specifications for the SRF were tested: linear (L), linear with interaction (LI), linear, quadratic, linear interaction (LQI), third degree polynomial with linear interactions (P3I), fourth degree polynomials with second degree interaction (P4I2), and fourth degree polynomial with fourth degree interactions and polynomial three-way interactions (P4I4S3). For nearly all models and specifications, the precision increased sharply as far as the LQI specification. In addition to the polynomial interpolations, some Chebyshev polynomials and basis-splines were tried, without significant further improvement.

In summary, it was found that the best functional form for fitting the surface of the surface response function was the linear-quadratic-interaction. They are therefore a reliable basis for the Monte Carlo simulations.

3.a Monte Carlo simulations. For the Monte Carlo simulations, the authors took the SFRs for each parameter/model§/year/policy and made 1,000,000 draws for each pdf for the three uncertain parameters. Then they examined the resulting distributions. These estimates are within-model results and do not include across-model variability. The results highlight that emissions, economic output, and damages have the highest degree of variation, implying that the uncertainty in these output variables is higher than for other variables, such as CO_2 concentrations and temperature.

Table 4 shows the distribution of global temperature increase in 2100 by model. The temperature distribution of the six models are remarkably close: the median ranges from 3.6°C to 4.2°C, with IGSM being the lowest and MERGE being the highest.

In examining the uncertainties of climate change and other topics, a typical approach has been to look at the difference s among forecasts, models, or approaches ("ensembles"), and to hypothesize that these are a reasonable proxy for the uncertainties about the final result or endogenous variables. Often, researchers have looked at the equilibrium climate sensitivities in different climate models and postulated that the scattering would be a precise measure of the effective uncertainty of the ECS.

The difference among models represents a measure of statistical uncertainty; for example, alternative climate models may have different ways of including cloud feedbacks. Taking the difference among the models would indicate the way in which state-of-the-art models differ on the processes and variables they include. Despite that, existing models are likely to have an incomplete understanding and will thus underestimate structural uncertainty. And they do not explicitly model parametric uncertainty. In IAMs, differences in models reflect differences in assumptions about growth rates, production functions, energy systems, and so on. But few models explicitly include parametric uncertainty about these variables. Differences in population growth, for example, are very small relative to uncertainty measures based on statistical techniques, since many models adopt the same estimates of the long-run population growth.

The authors use the results of a Monte Carlo simulation to estimate the relative importance of parametric uncertainty and model uncertainty. If we assume the outcome for variable i and model m is Y_i^m, and the uncertain parameters are u_i and u_j:

$$Y_i^m = \alpha_i^m + \sum_{i=1}^{3} \beta_i^m u_i + \sum_{j=1}^{3} \sum_{i=1}^{j} \gamma_{i,j}^m u_i u_j \tag{3}$$

For a given distribution of each of the uncertain parameters, the variance of Y_i including model variation is:

$$\sigma^2(Y_i) = \sigma^2(\alpha_i) + \sum_{i=1}^{3} (\beta_i^m)^2 \sigma^2(u_i) + \sum_{j=1}^{3} \sum_{i=1}^{j} (\gamma_{i,j}^m)^2 \sigma^2(u_i) \sigma^2(u_j) \tag{4}$$

The first term on the right hand side is the variance due to model differences or structural uncertainty, whereas the second and third term are the variance due to parameter uncertainty. Therefore we add the interaction of the model coefficients (β_i^m and $\gamma_{i,j}^m$) and the parameter uncertainties $[\sigma^2(u_i)]$ as parametric uncertainty, as they would not be included in the ensemble uncertainty. The other terms cancel out because they assume that the parametric uncertainties are independent.

Therefore, the authors estimate total uncertainty and the structural uncertainty for different variables. As a result, for most models all the variance is explained by parametric uncertainty.

Finally, a sensitivity analysis shows that the most sensitive variable is TFP, relative to population growth and equilibrium climate sensitivity.

In **Defining a sustainable development target space for 2030 and 2050** Van Vuuren, Zimm, Busch et al. 2022 define a target space and a scenario analysis for attaining the 17 sustainable development goals (SDGs) established by the UN General Assembly in 2015 for countries worldwide. They claim that quantitative goal-seeking scenario studies help explore thee needed systems' transformations. They thus propose a streamlined set of 36 science-based indicators and associated target values which are quantifiable and actionable to make scenario analysis meaningful. The longer-term reference point is 2050.

The SDGs are economic, social, environmental, and institutional objectives. They aim to ensure that development patterns may lead to well-being and social inclusion while maintaining the Earth's biophysical life support stability systems. Achieving the SDGs will require substantial transformation of actual societies. Hardly any information is present on how to achieve the various SDGs together, accounting for the linkages between them. For example, to achieve food security for all (SDG2), it is needed to increase production through intensive agriculture, which may lead to higher consumption of fertilizers and thus emissions of nitrous oxide (SDG13), or provoking water shortages (SDG6). In a similar fashion, using bioenergy to reduce green-house gases emissions (SDG13) might lead to an expansion of agricultural land, perhaps reducing biodiversity.

However, there are a lot of synergies, for example, reducing green-house gases through renewables (SDG13) reduces pollutants, thus improving health (SDG3). No studies have looked at attaining the whole 17 SDGs simultaneously or the longer-term implications, which is critical. Few exceptions are the Science-based Target Initiative and the UN Global Sustainable Development Report. Any attempt to provide a quantitative analysis of pathways towards achieving the SDGs would need a precise formulation on the target space, i.e. a limited set of targets expressed unambiguously and providing a comprehensive coverage of the ambition of the SDGs. Despite the current 169 targets and 232 indicators allow tracking global and country-level progress on applying the 2030 Agenda, they are too broad, unstructured, and complex to support quantitative analyses of transformation trajectories and are not always science based.

Consequently, progress on scenario development at all scale is slowed down by the absence of a simple scheme that includes all relevant, sustainable development dimension, that several science areas are relevant to the SDGs. Formulating a standardized target space could help the scientific community in analyzing trajectories towards meeting the SDGs. The community should work together with sets of models to provide a comprehensive analysis. The paper suggests a systematic target space formulation that allows for sustainable development scenarios and that can be tested and evaluated in scenario studies. The targets can be used to go beyond the more topic-oriented scenario analysis done so far, such as climate (Intergovernmental Panel on Climate Change [IPCC]), biodiversity (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [IBPES]), and food (Food and Agriculture Organization [FAO]) towards an integrated analysis of the people-planet framework. The set of objectives can be tested at the global, regional, national, and subnational level, providing hints to the usefulness and applicability of the set.

The creation of a target space draws upon the work of The World in 2050 (TWI2050) initiative. TWI2050 brings together scientists involved in scenario modeling, social and natural scientists, and policy analysts from all over the world for collaboration for the development and use of sustainable development pathways. TWI2050 identified six central transformations, outlining a group of actions for jointly reaching the SDGs and bringing forth sustainable development beyond 2030: (1) moving human capacities and demography forwards; (2) initiating responsible consumption and production trends; (3) reaching decarbonization and inclusive and sustainable energy systems; (4) establishing sustainable land use management and access to food while protecting biodiversity of terrestial and aquatic ecosystems; (5) developing sustainable cities and communities; and (6) aligning the digital revolution with the SDGs. Around 60 scientists were involved in TWI2050 and assisted in elaborating the target space. This implied the choice of the indicators and the associated target space.

There were several steps in the process: (1) conceptualization of key principles for the target space and selection criteria; (2) the review of existing groups of indicators and targets in the literature, international agreements, and associated with the SDGs; and (3) the final selection of a set of indicators and targets.

The criteria for defining the sustainable development target space are: (1) **societal relevance**; (2) the fact that the indicators should be **science based**[6]; (3) they should

[6]the indicators need to address the most relevant dimensions of human development (people), socio-economic well being (prosperity), national and international security (peace), and global environmental change (planet) as discussed in the scientific literature.

be **valid for 2030 and beyond**, accounting for path dependency; (4) they should be **quantifiable**; (5) **transparent**; (6) **actionable and achievable**; and (7) they should assure **availability of data and knowledge**.

The targets (SDGs), normative goals, and indicators for the 2030 and 2050 target spaces are:

(1) **no poverty** → end extreme poverty; the indicator is the number of people below international poverty line, which now is 889 million of people (13%); the target for 2030 and 2050 is 0;

(2) **zero hunger** → end hunger; the indicator is the number of people undernourished (below MDER); now there are 795 million (11%) people undernourished, and the target for 2030 and 2050 is 0; the other indicator is healthy diets for all, where the number of people with obesity (BMI$\geq$ 30) is 636 million (10%) in 2010, and the goal is 0 both for 2030 and 2050;

(3) **good health and well being** → achieve adequate health care for all; helath expectancy at birth (years) → global mean 63.12 years; under 5 mortality rate (deaths per 1,000 live births) → global mean 43; 99 in ub-Saharan Africa; for the first indicator the target is ≥ 65 for 2030, and ≥ 70 for 2050; for the second indicator the target is 25 for 2030, and 12 for 2050;

(4) **quality education** → universal lower secondary education → share of leaving cohort completing lower secondary education → the current situation around 2015 is 90% primary and 76.7% lower secondary completion rate → the goal is 80% secondary and 100% primary for 2030 and 100% secondary for 2050;

(5) **gender equality** → end gender discrimination in education → the gender gap in years of schooling of population aged $\geq$ 15 years → global mean 0.79, target 0 for both 2030 and 2050; achieve gender pay parity → female estimated earned income over male → 52%-87%, goal 0 for both 2030 and 2050;

(6) **clean water and sanitation** → universal access to clean water → population without access to improved water source piped → 660 million (9%) → goal 0 by 2030 and 2050; universal access to sanitation → population without access to improved sanitation facility → 2.4 billion (32%) → objective 0 by 2030 and 2050; end water scarcity → the area under water stress (water stress index for most water scarce month/season) → 11% → goal no increase;

(7) **affordable and clean energy** → universal modern energy service for all → population cooking with traditional biomass → 2.8 billion (37%) →goal 0 by 2030 and 2050; population without basic electricity access → 1.1 billion (13%) → goal 0;

(8) **decent work and economic growth** → work for all → unemployment rate (formal economy) → 6% → objective 6%; global economic convergence → the ratio of GDP per capita of a country to the average OECD GDP per capita (both in PPP) →average low-income countries: 5.0% middle-income countries: 16.7% (both 2018) → low-income countries: 2-fold increase; lower-middle-income countries: increase by 50% by 2030; low-income countries:4-fold increase (reaching at east 15%); lower-middle-income countries: 3-fold increase;

(9) **industry, innovation and infrastructure** → R&D → R&D intensity, i.e. private and government-financed gross domestic R&D ependiture (GERD) in percent

GDP → current situation 1.7% → 2030 target 3%; 2050 target 3%; universal access to ICT → the proportion of the population using the internet → current situation 46% → 2030 and 2050 target 95%; universal access to finance → the proportion of the adult population with an account at a financial institution → current situation 69% → 2030 target middle- and high-income countries: 90%; low-income countries: 80%; 2050 target 95%; fast access to an economic hub → travel time to the nearest city with at least 50,000 inhabitants → current situation, high-income countries: less than 1h for 90% of the population; low-income countries: 20% have to travel for more than 3h → 2030 target: middle and high-income countries: less than 1h for 90% of the population; low-income countries: less than 3h for 90% of the population; 2050 target: all countries: less than 1h for 90% of the population;

(10) **reduced inequalities** → decrease relative poverty → number of people below 50% of the median national daily income (% of the population) → current situation: > 1.4 billion ($\sim 20\%$) people; → 2030 target 15%; 2050 target 10%;

(11) **sustainable cities and communities** → decent housing for all → population living in slums (urban) → current situation: 880 million (30% of urban population); 2030 target: 10%; 2050 target:0; improve air quality in cities → population exposed to annual average PM2.5> $25\mu g/m^3$ → current situation: 65%; 2030 target: 20%; 2050 target: 10%;

(12) **responsible consumption and production** → reduce waste and pollution → food loss and waste → current situation: 33%; 2030 and 2050 target: $< 15\%$; municipal material recovery → 34% in OECD; 2030 target: 59% (top 5 countries 2015); 2050 target: - ;

(13) **climate action** → limit global warming → well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels → current ituation: 55 $GtCO_2$ eq → 2030 target pathway towards long-term goal; or globally at least below $< 27 - 40 GtCO_2$ eq (1.5 and below 2°C, 50th percentile); 2050 target: pathway towards long-term goal; or globally below $< 7 - 18 GtCO_2$ eq (1.5 and below 2°C, 50th percentile);

(14) **life below water** → balance phosphorus in oceans → P flow from freshwater systems into the ocean → curreent situation: $\sim 22 TgPy - 1$; 2030 and 2050 target: 11 $TgPy - 1$; sustainably manage marine resources → the proportion of fish stocks within biologically sustainable levels → current situation: 65%; 2030 target: 90%; 2050 target: 100%;

(15) **life on land** → halt land-system change (deforestation) → global: area of forested land as % of original forest: area of forested land as % of potential forest → current situation ∼ 4,000 ha; 2030 target: no further loss of primary forest; 2050 target: global: 75% (75%-54%), specified by forest type; balance nitrogen in soils → industrial and intentional biological fixation of N → current situation: $\sim 150 TgNy^{-1}$; 2030 and 2050 target: 62 $TgNy^{-1}$; protect biodiversity → BII → 2030 and 2050 target: no degradation from 2020 onwards;

(16) **peace, justice, and strong institutions** → reduce violence and related deaths → battle-related deaths and fatalities from one-sided violence → current situation: $> 93,000$; 2030 and 2050 target: 0 per country/year; promote the rule of law and

ensure equal access to justice for all → equality before the law and individual liberty-index → current situation: global: 0.69 (based on Coddepdge et al.); 2030 and 2050 target: increase all individual country score, at least > 0.9; ensure responsive, inclusive, participatory, and representative decision-making → equal access index → current situation: global: 0.63 (based on Coppedge et al.); 2030 and 2050 targets: increase all individual country scores, at least 0.9;

(17) **partnership for the goals** → increase statistical capacities → statistical capacity score: source data (second dimension of the Statistical Capacity Indicator by the World Bank) → current situation: 62.0 (global average for 149 countries); 2030 and 2050 targets: increase up to 100 for all countries; strengthen domestic resource mobilization → total government revenue → current situation: global average 24%-28% (w/o natural resources) for 2011-2015 (based on ICTD/UNU-WIDER); 2030 target: increase to 20% for countries currently below the threshold, otherwise, maintain; 2050 target: maintain the level of 2030 the threshold without the revenue generated by the exploitation of natural resources; enhance interconnection with global civil society → number of international NGOs of which a country is member, whether directly or through the presence of members in that country → current situation: global average 386 (based on UIA, countries $< 500,000$ excluded); 2030 target: increase value above the 25th percentile based on data for 2017 for countries below this threshold, otherwise maintain; 2050 target: increase value above the 25th percentile based on data of 2030 for countries below this threshold, otherwise maintain;

most targets can be applied at the regional or national level; MDER, minimum dietary energy requirement; BMI, body mass index; PPP, purchasing power parity; ICT, information and communication technology; PM2.5, fine particulate matter smaller than 2.5 micron; P=phosphorous; N=nitrogen; BII, biodiversity intactness index; NGOs, non-governmental organizations.

In **Integrated Assessment Models of Climate Change**, William Nordhaus 2017 claims that many areas of the natural and social sciences regard complex systems linking various areas and disciplines; this is particularly true for the science, economics, and policy of climate change, which involve a wide variety of fields, from atmospheric sciences to game theory. It is increasingly important to link various fields to develop models and policies taht reflect taht economic activity regulates the emissons, which influence atmospheric concentrations, thus climate and the hydrological cycle, which therefore affects human and natural systems, which finally contribute to shape climate policies.

Integrated assessment analyses and models cover a pivotal role putting the pieces together. Integrated assessment models integrate knowledge from two or more areas into a single framework. They are sometimes theoretical, but are increasingly computerized, empirical, dynamic, non-linear models of different degrees of complexity.

The contest with global warming is particularly difficult to deal with because it involves many disciplines and segments of society. Ecologists might see it as a threat to ecosystems, marine biologists as a problem provoking ocean acidification, and coastal communities as a lottery with harsh hurricanes, while ski resorts may view it as a deadly danger to their already short seasons.

Integrated assessment models of climate change initially evolved from energy models; one of the earliest comparisons of energy models was the Modeling Resource Group (MRG) analysis of the 1970s. The Nobel prize winning economist Tjalling Koopmans promoted the analysis of several energy models projecting energy demands and technologies over a long time-span. The core of these energy models was the linear programming approach by Koopmans as well as the Samuelson principle of "markets as maximization".

The first IAMs were basically energy models with an emissions model contained therein, and lter with other modules such as a carbon cyce model and a small climate model. Nordhaus' early approaches were partial equilibrium energy models with exogenous output. A. S. Manne's model was an important stepping stone; it embedded an energy system in a full economic growth model, and Nordhaus' first models were similar to that, extending it to geophysical variables.

IAMs are more and more used in analyses by national governments and in international assessments; among the most relevant applications are:

- making projections having strong inputs and outputs of the various components of the system;

- computing the effects of alternative assumptions on relevant variables such as output, emissions, temperature change, and the impact of economic activity on climate;

- tracking the impacts of alternative policies on all variables in a coherent way, as well as evaluating the costs and benefits of alternative plans of action;

- calculate the uncertainties linked with alternative variables and strategies, jointly with the value of new research and new technologies.

The dynamic integrated climate economy model (DICE) and the regional integrated climate economy model (RICE) are updated regularly, with the latest update dating 2023, since their initial development in the early 1990s. They are available in GAMS and MATLAB. The DICE model is globally aggregated, while the RICE is structured in 12 regions; the DICE model views the economics of climate change from the viewpoint of neoclassical growth theory. Economies make investments if capital, education, and technologies, thus reducing consumption today to increase consumption in the future. The DICE model includes the "natural capital" of the climate system. By reducing the emissions through output, economies reduce consumption today but avoid economically harmful climate change and thus raise consumption chances in the future.

The DICE model has 12 behavioural equations, two optimizing variables, and several identities. The GAMS version has 240 lines of operational code, in the basic version, which takes five seconds to run 1,000 years of projection, therefore it can be used to project multiple states of the world and Monte Carlo simulations.

The RICE model has the same basic economic and geophysical structure, but involves a regional elaboration. The preferences are specified in different ways since it includes various regions. The general preference is a Bergson-Samuelson social welfare function over regions. The solution method is the Negishi approach, where regions re joined using time and region-specific weights subject to budget constraints.

These IAM models can be called geo-macroeconomics. Small models can be fast and can easily adapt to a changing environment or new data, while large models take many years to mature, but can handle much larger and more complex tasks. The various policies analyzed by the DICE are, for example:

- *baseline* → no climate policies adopted;

- *optimal* → climate change policies maximize welfare, with full participation by all nations starting in 2020;

- *temperature-limited* → the optimal policies are implemented subject to further constraint that global temperature does not exceed 2.5°C above the 1900 average (the international goal of 2°C is not feasible with current DICE estimates without technologies that allow negative emissions by mid 21st century);

- *Stern discounting* → these are results linked to an extremely low discount rate as advocated by the Stern Review;

The outcomes associated with the four different policy options show that emissions differ sharply, with major cuts in emissions in cases with ambitious policies; then, the temperature in the uncontrolled case continues to rise sharply over the current century.

Concerning the price of carbon in the different scenarios, this method measures the marginal costs of reductions of emissions of GHGs; in a system such as a cap-and-trade regime, the carbon price would be the trading price of carbon emission permits. In a carbon tax regime, they would be the harmonized carbon tax among participating regions. Carbon prices in the baseline case are the current mean prices in world markets, about 2$ per ton of CO_2; prices under the optimal and temperature-limited scenarios at first rise to 35$ and 229$ per ton of CO_2, respectively, by 2020.

The carbon price is strictly linked to an important policy instrument, the social cost of carbon (SSC). This represents the economic cost of an additional ton of carbon dioxide emissions or its equivalent. IAMs can calculate the shadow price of carbon emissions along a typical path of output, emissions, and climate change. In an optimized climate policy, the social cost of carbon would equal the carbon price or the carbon tax.

In **Cost and attainability of meeting stringent climate targets without overshoot**, Riahi, Bertram, Huppmann et al. 2021 of the International Institute for Applied Systems Analysis (IIASA) of Vienna develop alternative configurations of net-zero CO_2 emissions systems and outline the roles of different sectors and regions for balancing sources and sinks. Even without net-negative emissions, CO_2 subtraction is important for accelerating short-term reductions and for providing an anthropogenic sink that can compensate the residual emissions in sectors that are hard to abate.

The framework for international climate action are set forth in the Paris Agreement. Countries attempt to keep global warming well below 2°C and pursue limiting it to 1.5°C. Studies explore features of the timing and costs of emissions reductions and the shares of different sectors. Despite that, there has been a critique that the scenarios in the literature exceed the outlined temperature limits in the hope of regaining land from this overshoot through net-negative emissions. Some studies have dig into the implications of limiting overshoot through zero emissions aims, or have explored the role of bioenergy with carbon capture and storage in attaining different temperature targets.

The authors take together nine international modeling groups and carry on a comprehensive modeling intercomparison project (MIP) on this theme. They explore mitigation pathways for reaching different temperature change targets with limited overshoot. They do this by adopting the scenario design of Rogelj et al. 2019 (Nature), and compare scenarios with a fixed remaining carbon budget until the moment in which net-zero CO_2 emissions (net-zero budget scenarios) are reached with scenarios that use an end of century budget design. The latter carbon budget for the full century allows the budget to be temporarily overspent, as far as net-negative CO_2 emissions bring back cumulative CO_2 emissions to within the budget by 2100. This approach is mostly adopted by the current literature, and leads to a temporary overshoot of the associated temperature target. In particular, the earlier brought into use "net-zero budget scenarios" limiting cumulative CO_2 to a maximum without exceeding the emissions budget. These scenarios thus keep global warming below a certain threshold (without exceeding it) and stabilize the temperature thereafter.

The new pathways fill important knowledge gaps. First, they deal with the range of carbon budgets consistent with low stabilization targets in a systematic way and across a wide range of diverse global models. The pathways thus explore important uncertainties, including the attainable scenario space across different models and target definitions. This information is crucial for international assessments such as those by the IPCC. Secondly, they explore the country promises from the post-Paris process for the attainability of overshoot and non-overshoot targets. Thirdly, they investigate salient temporal trade-offs in relation with mitigation costs; finally they explore variations on the possible regional and global designs of net-zero CO_2 emissions systems.

Attaining narrow temperature targets with limited overshoot, necessitates a significant acceleration of near-term transformations towards net-zero CO_2 emissions. Remaining within a budget of 500 $GtCO_2$, for example, requires CO_2 emissions to reach net-zero between 2045 and 2065 (range across models). When and "end-of-century" carbon budget is adopted, the time of reaching net-zero CO_2 emissions is delayed between 5 and 15 years (to 2060-2070). This delay, combined with the higher emissions over that period, results in 0.08-0.16°C higher peak temperatures compared to scenarios that are identical in all but their allowance to overshoot the carbon budget.

A broad set of behavioural, biophysical, economic, geophysical, legal, political, and technological factors make turning to net-zero more challenging. The modeling exercise here regards particularly challenges related to economic, geophysical, and technological feasibility. The lowest attainable net-zero CO_2 emissions budget (limiting overshoot) is 400-800 $CtCO_2$ across the models (assuming immediate application of ambitious policies and a middle-of-the-road socio-economic development[7]). This budget range corresponds to a median peak warming during the twenty-first century between 1.42 and 1.72°C.

Weak near-term policies that result in higher GHG emission over the next decade, such as those implied by the current nationally determined contributions (NDCs), will affect the lowest attainable carbon budget. They authors estimate that the NDCs will lead to GHG emissions of 46.8-56.3 $CtCO_2e$ by 2030, which is substantially higher than the range of cost-effective emissions pathways consistent with 2°C (25-48.6 $CtCO_2e$), not to mention the 1.5°C by 2030 (19.4-35.3 $GtCO_2e$). The authors assume the definition of 1.5°C and 2°C goals from the SR1.5. Assuming NDCs are not tightened and compre-

[7] O. Fricko et al., The marker quantification of the Shared Socio-economic pathway 2: a middle of the road scenario for the 21st century, Global Environmental Change, 2017

hensive climate policies are thus delayed until after 2030, the lowest attainable net-zero CO_2 budget across models is 500-1,200 $CtCO_2$, which corresponds to a warming of 1.61 and 1.89°C. Current NDCs thus put limiting warming to 1.5°C out of reach on the basis of the biophysical, economic, geophysical, technological feasibility dimensions reflected by the models applied here. Other feasibility dimensions, such as behavioural, legal, political, or social aspects, can affect this ranges further, even though this study does not explore their impact.

The pathways features net-negative emissions from a few mega-tons to ~ 500 $GtCO_2$ across models, showing a techno-economic potential for declining warming after its peak between 0.13 and 0.34°C by 2100. This temperature reversal is mainly driven by non negative carbon emissions but can also partially be outcome of reductions in non-CO_2 forcers.

The net-zero budget scenarios allow for the systematic quantification of the residual non-CO_2 emissions, consistent with different peak temperature levels; most of these non-CO_2 emissions is caused by the agriculture, forestry, and other land-use (AFOLU) sector, in particular by enteric fermentation (CH_4) and fertilizer use (N_2O); the annual residual non-CO_2 emissions in the second half of the century range from slightly above 3 to $> 10GtCO_2e$, highlighting once more the dual importance of CO_2 and non-CO_2 mitigation measures.

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