Climate economics support for the UN climate targets

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Abstract

Under the UN Paris Agreement, countries committed to limiting global warming to well below 2°C, and to actively pursue a 1.5°C limit. Yet, according to the 2018 Economics Nobel laureate William Nordhaus, these targets are economically suboptimal or unattainable and the world community should aim for 3.5°C in 2100 instead. Here we show that the UN climate targets may be optimal even in the DICE integrated assessment model, when appropriately updated. Changes to DICE include more accurate calibration of the carbon cycle and energy balance model, and updated climate damage estimates. To determine economically "optimal" climate policy paths, we use evidence on the range of expert views on the ethics of intergenerational welfare. When updates from climate science and economics are considered jointly, we find that around three-quarters (one-third) of expert views on intergenerational welfare translate into economically optimal climate policy paths that are consistent with the 2°C (1.5°C) target.

Limiting global warming to well below 2°C (let alone 1.5°C) as decided in the UNFCCC Paris Climate Agreement is either unattainable or far from the economic optimal according to William Nordhaus[1]. Instead, his economic analysis implies a climate policy path that limits global warming to 3.5°C by the end of the century and decarbonizes the economy only in the next century. According to Nordhaus, this reflects the economically optimal balance between future benefits and current costs. So while both the UN climate targets and Nobel Prize winner highlight the need for a policy response to global climate change, they are strikingly different in the stringency of the recommended temperature goals and the implied emission pathways over the century[2,3].

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Nordhaus' recommendations are derived from the DICE integrated assessment model (IAM), which he created and developed in several steps[4,5]. The model seeks to find the optimal emission, temperature and carbon tax trajectories by balancing the costs of emissions reductions and the damages of climate change, measured in economic terms. Emissions reductions are justified provided the benefits of avoiding climate damages outweigh the costs, e.g. higher costs associated with energy supply. Nordhaus was early in making his model readily available to the research community and it has become central in climate economic analysis and highly influential in policy discussions[6-8]. However, DICE has also been criticized on a number of grounds. These include the choice of discounting parameters[9-11], the model's omission of uncertainty and the risk for climate catastrophes[12-15], the treatment of non-market damages[16,17], and details of its climate model[18-20]. Notably DICE's concept of economic optimality, i.e. maximizing a Discounted Utilitarian social welfare function, has been criticized for not reflecting the structure of optimal-control models that incorporate risk and uncertainty[15], and for its reliance on a single conception of intergenerational welfare[21-24]. DICE has also been subject to general criticism regarding the use of cost-benefit analysis for climate policy purposes[25-27].

The Committee for the Prize in Economic Sciences in Memory of Alfred Nobel was well aware that the precise conclusions that Nordhaus draws from DICE are highly sensitive to specific assumptions. In its scientific background paper, the Committee stated that the 2018 Laureate was rewarded for the methodological contribution of integrated assessment modelling, not the specific policy recommendations following from DICE's baseline calibration. In this Analysis, we show that updates to the existing parameters of the DICE model, drawn from some of the latest contributions in social and climate science, lead to economically optimal climate policies and emissions pathways that are in line with the UN climate targets.

Specifically, our updates to the basic DICE parameters draw from the latest findings on economic damage functions[28], which Nordhaus[1] includes in a sensitivity analysis, together with some of the latest climate science[29,30], and a broad range of expert recommendations on social discount rates[24]. This is complemented by revised assumptions regarding non-CO_2 greenhouse gas emissions[31], the feasibility of negative emission technologies[2,32], and constraints on the feasible speed of decarbonization[2,33]. While some of these individual updates have already been analyzed in the existing literature, our innovation is to analyze their joint effect in DICE. This reveals that there is no inherent discrepancy between the method underpinning the 2018 Economics Nobel Prize and the UN climate targets.

Updates to the Climate Module

Our first major update of the DICE model serves to better reflect the relationship between emissions, concentration and temperature change. The climate module in the most recently available version of DICE-2016R2[34] has two key limitations. First, DICE uses a linearized carbon cycle model. This linearization has been undertaken for cumulative CO_2 emission levels far higher than those compatible with the UN climate targets[5]. Consequently, the impact on CO_2 concentrations of each emissions pulse is overestimated for any scenario in which cumulative emissions are smaller than those found Nordhaus' optimal analyses[34,35]. Second, the energy balance model that is used to calculate the temperature impacts of radiative forcing in DICE is not in line with the most recent advanced climate system models.

We first update DICE by implementing the carbon cycle module from the simple climate model FAIR[29,30]. This module takes into account how the removal rate of atmospheric CO_2 depends on past cumulative CO_2 emissions and changes in the global mean surface temperature. The FAIR model was central for the assessment of emission pathways in the IPCC Special Report[36] on 1.5°C warming[2].

To further improve the energy balance model in DICE, we recalibrate it so that its response approximates the results of advanced climate system models included in the Coupled Model Inter-comparison Project 5 (CMIP5)[37]. The findings of CMIP5 were central for the climate system model characterizations in the IPCC's Fifth Assessment Report[38]. Geoffroy et al.[37] fit simple two-box energy balance models to larger climate system models and show that these simple models capture the global aggregated temperature dynamics of the large-scale climate system models. We use the findings of Geoffroy et al.[37] to recalibrate the two-box energy balance model in DICE and thus make its temperature dynamics consistent with recent climate science.

The climate sensitivity that determines the equilibrium temperature change for a given change in radiative forcing in DICE is set to 3.1°C for a doubling of the atmospheric CO_2 level[5]. As this remains consistent with the most recent central estimates of equilibrium climate sensitivity[39,40], we leave it unchanged.

These updates roughly align our temperature pathways for a given emission scenario with median estimates generated by simple climate models (FAIR and MAGICC) used in the IPCC Special Report on 1.5°C warming[2,41] and in the UN Emissions Gap Report[3]. See Methods and Extended Data Fig. 1, 2, 5 and 6 for how the carbon cycle and EBM updates, respectively, affect the optimal pathways. With these changes, lower temperature scenarios become attainable, and the optimal temperature change by 2100 drops by half a degree compared to the original DICE calibration, to just below 3°C by the end of this century.

Updates to the Economics

The optimal policy response in DICE is notoriously sensitive to two socio-economic inputs: the social discount rate and the magnitude of economic damages incurred as temperatures increase. The damage function has proven difficult to estimate because of the joint uncertainties of physical climatic effects, the likely socio-economic responses to these effects, and the economic valuation of these damages. Since the first attempts to estimate economic damages for different temperature levels[4,9,42-44], methodologies have improved, but key challenges remain[45]. For instance, the quadratic damage function used in the standard DICE is calibrated to a meta-analysis[46] that has been shown to suffer from multiple citation bias, a form of non-independence[28]. We instead use the damage function of Howard and Sterner[28], who provide an up-to-date meta-analysis of the quadratic temperature-damage relationship that corrects for the problem of non-independence. In what they refer to as their "preferred model", damages are substantially higher than in the original DICE model, reaching 6.7% of global GDP for a 3°C temperature increase, as compared to 2.1% in the standard DICE[34]. This updated damage function is closer to, yet still more conservative than, recent micro-econometric studies[47] and expert elicitations on the topic[48,49], which estimate damages upwards of around 10% of global GDP for a 3°C temperature increase. In our central model, we do not change the functional form of the damage function, as in Weitzman[12,50] or Glanemann et al.[51], who apply the damage function of Burke et al.[47], but rather update how damage estimates are combined to calibrate the standard DICE damage function. When using our updated damage function alongside the improved calibration of the carbon cycle and energy balance model, leaving DICE otherwise unchanged, optimal temperature is reduced by a further 0.8 degrees to 2.2°C by 2100. For robustness, we also undertake a simulation of the Weitzman[50] damage function, which has higher order polynomial terms. The details of how this recalibration affects the model results can be found in the Methods and Fig. S3 in the additional Supplementary Information.

Next, we consider the determinants of intergenerational welfare as embodied in the social discount rate (SDR). The SDR captures the ethical choices involved when policies transfer well-being between current and future generations[11,52,53]. The SDR can be simultaneously viewed as embodying conditions on fairness and economic efficiency across generations. Again, we do not change the structure of the DICE model, and our updates calibrate parameters of the standard Discounted Utilitarian social welfare function used in DICE: the pure rate of time preference and the elasticity of marginal utility (See Box 1). Other studies have changed the structure of the social welfare function by separating out the coefficient of risk aversion and the elasticity of intertemporal substitution, for instance. Indeed, there are many different ways in which social welfare could be measured[24]. Box 1 presents further details on DICE's Discounted Utilitarian social welfare function, including extensions that incorporate risk and uncertainty[15,54-56].

Climate policy recommendations are very sensitive to the choice of discount rate. Subjective ethical perspectives underpin often irreducible differences of opinion on the matter, making the choice of SDR the subject of disagreement. To inform policy it is therefore important to understand the extent of disagreement. For this reason, we update the DICE model by using the latest evidence on expert recommendations on the SDR. Drupp et al.[24] surveyed 173 experts on what Nordhaus[57] referred to as the two "central normative parameters" that determine the SDR: the pure rate of time preference and elasticity of marginal utility. The survey responses contain both positive and normative viewpoints on these parameters. By using these data, we move away from the simple black and white characterization of social discounting that is usually framed in terms of the Stern versus Nordhaus debate, and engage with the full range of expert recommendations.

We employ two approaches to summarizing the range of expert recommendations for policy purposes. First, we consider the climate paths associated with each expert's chosen pair of discounting parameters and take the median ("median expert path") of all 173 model runs for the SCC, temperature and emissions at each point in time. Second, we consider the median response for each of the two discounting parameters separately ("median expert view"). Both approaches have a theoretical justification in the literature on voting outcomes (see Methods), and hence imagine a voting solution to the disagreement on the SDR[58-60] .

Both approaches place greater weight on future generations' well-being compared to Nordhaus' calibration, leading to more stringent climate policies. Compared to the original DICE using Nordhaus' discounting parameters, the optimal temperature is reduced by 0.5°C and 1.1°C according to the "median expert path" and the "median expert view" respectively. When combined with the previous updates to the climate science and the damage function, the optimal temperature increase above the pre-industrial level falls from 2.2°C by 2100 in the case of Nordhaus' discounting parameter choices, to 2.0°C under the "median expert path". The temperature change under the "median expert view" is even lower at 1.7°C.

Box 1: Details on social/intergenerational discounting

Economic “optimality” in DICE relates to an optimal consumption and emissions path that results from maximizing an inter-temporal Discounted Utilitarian welfare function subject to economic and climate constraints. Specifically, intergenerational welfare in DICE is the discounted sum of utilities at each point in time where utility is discounted at the pure rate of time preference δ, and marginal utility diminishes by η% with each 1% increase in consumption. That is, η is the (absolute) elasticity of marginal utility. Depending on the parameterization of intergenerational welfare and on the constraints, many different paths of consumption and associated climate policies may be considered “optimal”. The social discount rate for consumption in this framework depends on both parameters and is given by the simple Ramsey rule:

$$\text{Social discount rate} = \delta + \eta * g, \tag{1}$$

where g the growth rate of consumption. According to the rule, δ and $\eta * g$ reflect two distinct reasons for discounting future consumption.

The pure time preference, δ, specifies how impatient society is (a positive approach) or should be (a normative approach) when waiting for future well-being. A pure time preference of 1.5% per year (or 0.5%) implies that the well-being of someone 100 years from now would be valued 77% (39%) less than the well-being of someone living today. These values correspond to the value judgement of Nordhaus and the median expert from Drupp et al.[24], respectively. Many believe that all generations should be weighted equally (δ = 0%). Others have argued for positive values to account for the small risk of humankind’s extinction (e.g. δ = 0.1%)[11], because non-discrimination may demand unacceptably high saving from the current generation[61], or because impatience is reflected in real rates of return on capital markets[52].

η can also be interpreted as measuring inter-temporal inequality aversion. Due to diminishing marginal utility, the idea is that an additional 1$ is worth more to a poor person than a rich one. In a growing economy, citizens in the future will be richer and their lower marginal utility motivates discounting. Suppose the economy grows at 2%. People living in 100 years will be seven times richer. If inequality aversion is the only reason for discounting, if η = 1 (1.45), which corresponds to the values of the median expert (Nordhaus), the value of $1 in 100 years is only 14 (6) cents. To estimate this parameter experts use introspection, experiments, surveys, revealed evidence from tax schedules and savings decisions[62]. More generally, η can also reflect risk aversion and the desire to smooth consumption over time.

The simple Ramsey rule (1) is used for project appraisal by a number of countries and organizations, including the Fifth Assessment Report of the IPCC[38]. However, the rule has various extensions that experts recommend[24]. A notable class of extensions relate explicit incorporations of risk and uncertainty[15,56,63,64]. Inspired by the finance literature, some of these approaches combine insights from asset pricing with climate economics and allow for differences in how much society is willing to substitute consumption risk across states of nature (risk aversion) compared to over time (inequality aversion). While noting these important extensions, we constrain ourselves to the welfare function used in the DICE model and solely perform parametric updates.

Further updates

We next make two further changes to align DICE with the larger scale models used to develop emission pathways that are assessed in terms of their likelihood to meet the 1.5°C and 2°C limits in the recent IPCC Special Report on 1.5°C[2].

First, the original DICE model assumes an exogenous radiative forcing for non-CO_2. This pathway for the non-CO_2 emissions is high compared to those generated by technology-rich IAMs reaching temperature targets in line with those in the Paris agreement[65]. We adjust DICE by taking the pathway for non-CO_2 forcers estimated by the REMIND integrated assessment model using the central Shared Socioeconomic Pathway (SSP2) that meets a radiative forcing level of 2.6 W/m^2 in 2100[31]. This higher abatement of non-CO_2 greenhouse gases makes even lower temperatures attainable. Among these paths we show that Nordhaus' view on discounting yields (using the updated DICE model) an optimal temperature increase of 2.0°C by 2100, and that reaching the 1.5°C climate target in 2100 (with some temporary overshoot) would be optimal according to the median expert's view. In contrast, the median expert path would imply global warming of 1.8°C by 2100.

Second, we consider the role of negative emission technologies (NET). Nordhaus[34] only allows for net-negative CO_2 emissions after 2160, while Nordhaus[1] allows for the possibility of NETs within this century. Removing CO_2 from the atmosphere by Carbon Dioxide Removal technologies such as Biomass Energy with Carbon Capture and Storage (BECCS), afforestation, and Direct Air Capture have been suggested as a possible critical and cost-effective abatement option to limit climate change[2,35,66-68] . The timing of the availability of negative emissions technologies and their potential magnitude are under debate[69,70], as well as their relation to the use of different discount rates[71] . Although we are aware of biophysical and socio-economic limits to all individual NETs, here we assume NET potentials by 2050 in line with the recent literature[36,69]. Feasibility will largely depend on reliable institutions, good governance and structured incentives across the innovation cycle as well as the implementation of a NET portfolio that overcomes the risk of relying on a single NET like BECCS[32,69]. The majority of emission pathways that stay below 2°C warming in the Working Group 3 of IPCC's Fifth Assessment Report[32,33] and the recent IPCC Special Report[2] have net negative CO_2 emissions during the second half of this century. We allow abatement of CO_2 to be at most 120% of the baseline emissions, as assumed by Nordhaus[34], but allow for the possibility of net negative CO_2 emissions from mid-century onwards instead of from next mid-century. This update results in optimal negative emissions of 18 $GtCO_2$ per year in 2100 at the lower 95% bound of expert recommendations on the social discount rate. The emission pathways that are assessed in the IPCC Special Report and that meet the 1.5°C level by 2100 have a median emission level of -12 $GtCO_2$ in 2100, with a lower 90% bound of -20 $GtCO_2$ per year as estimated from data available in the Integrated Assessment Modelling Consortium (IAMC) 1.5°C scenario explorer[72]. Allowing for NETs from 2050 lowers optimal temperatures but when introduced on top of our previously described changes to DICE, the effect on our two central runs is small: less than 0.1°C for both the median expert view and path.

Finally, DICE does not include constraints on the speed of emission reductions. Under Nordhaus'[34] calibration this is not a concern since emission reductions occur relatively gradually. However, in our updated version of DICE, the optimal policy path displays very fast rates of emission reductions. Yet, there are practical limitations on how rapidly a transition to a decarbonized world economy can be implemented[73]. Typically, these restrictions are incorporated into an integrated assessment model either by imposing a cost on the adjustment pace[74], or by technology inertia constraints[75]. We impose a set of constraints on the maximum rate of decarbonization. First, we set the starting emissions to 2020 levels. We also constrain the increase in emissions reductions between 2020 and 2045 to no more than 2 $GtCO_2$ per year. This constraint is consistent with the upper range of emission reductions used for assessing the 1.5°C and 2°C limits in Clarke et al.[33] and Rogelj et al.[2]. Finally, to avoid unrealistic emission reduction jumps for the period when negative emissions are feasible (2050 onwards), we limit the growth rate of the emissions reduction to 10% of the previous (5 year) period's emissions reduction. Fig. 1 summarizes the sequential updates within a schematic structure of the DICE integrated assessment model.

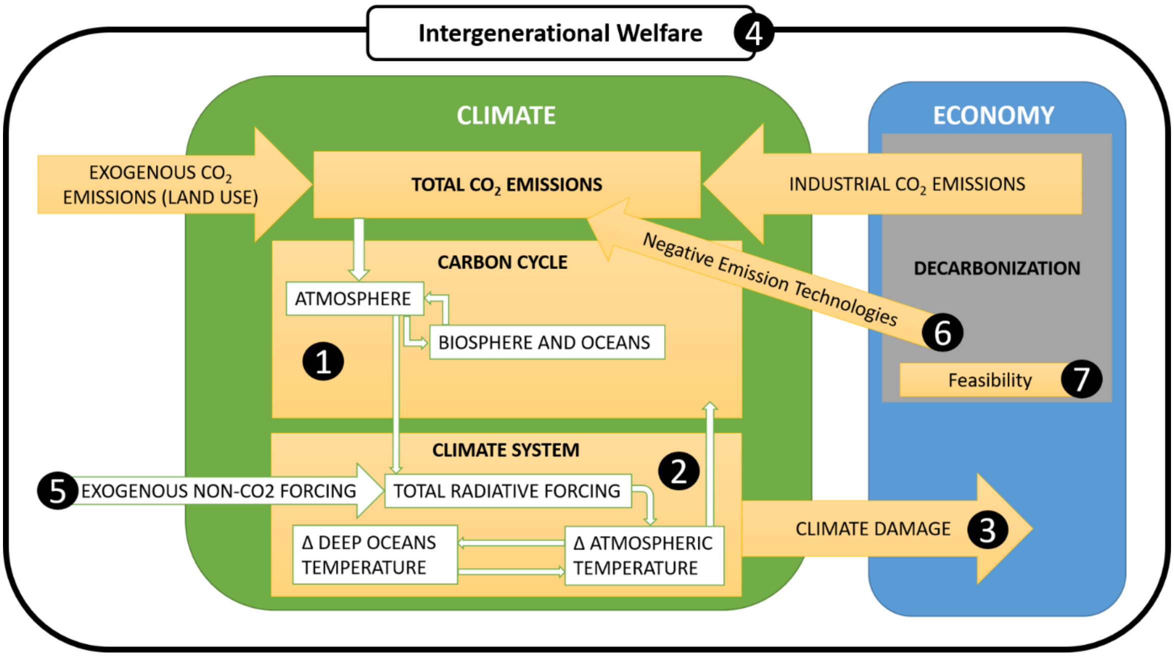

Figure 1. Updates to the climate-economy DICE model. *A stylized schematic of the DICE integrated assessment model that highlights the seven updates we make to the standard DICE version (2016R2[34]). These are: (1) A carbon cycle based on the FAIR model[29,30], (2) an update of the energy balance model[37], (3) a revised economic damage estimate[28], (4) a range of expert views on intergenerational welfare[24], (5) non-CO2 forcing in line with lower emission pathways[31], (6) the earlier availability of negative emission technologies[2], and (7) constraints on the maximum rate of decarbonization[2,33].*

A central ground for climate policy

Fig. 2 summarizes the optimal climate policy paths taking all the above-described changes to DICE into account. Since individual disagreements on value judgments embodied in the discounting parameters may be largely irreducible[76,77], we run the DICE model for each expert's view on the two discounting parameters to obtain 95th and 66th percentile ranges of optimal climate policy outcomes. Versions of Fig. 2 for each sequential stage of our adjustment to DICE are given in the Methods and Extended Data Fig. 5-9.

When expert views of the rate of pure time preference and inequality aversion[24] (Fig. 2A) are translated into global social cost of CO_2 emissions (SCC) in US$ per ton of CO_2 (Fig. 2B), the highest SCC for 2020 in the 95 percentile range is $520. By contrast, the lowest SCC in the 95-percentile range is $17. Nordhaus' discounting parameters imply a SCC of $82 in 2020 in our updated DICE, which compares to a SCC of $39 in the original DICE (see Fig. S1B in the additional Supplementary Information). By contrast, the median expert view translates into a SCC of $208. The median path in turn results in a SCC of $101. In sum, the social cost of carbon is at least twice as high as in the original DICE calibration.

There is a substantial range of resulting pathways of global fossil fuels related CO_2 emissions per year (Fig. 2C). In the central 66% range, the economy is decarbonized between 2055 and 2100. Given Nordhaus' choice of discounting parameters, the economy would be decarbonized within this century, by 2090, while optimal decarbonization takes place by 2065 with the median expert's view. The median path in turn results in decarbonization by 2080.

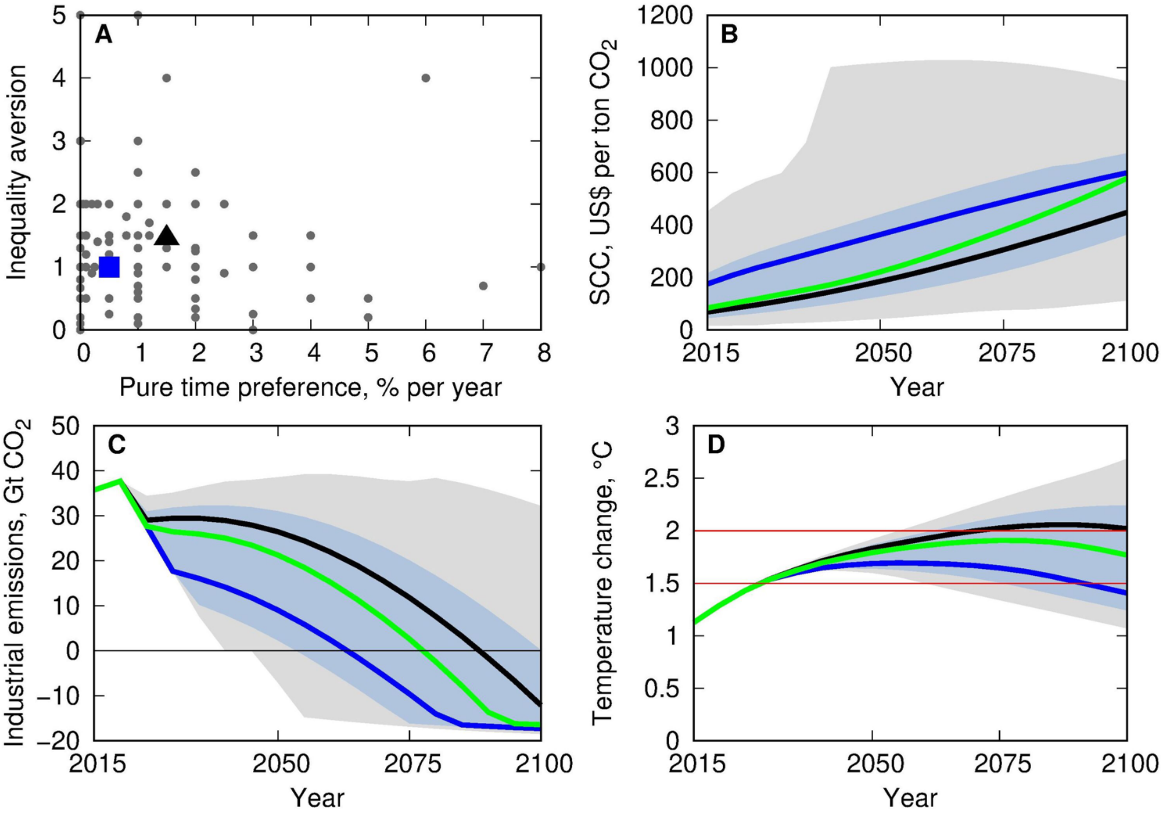

Figure 2. Climate policy pathways in the updated climate-economy model DICE. ***A*** *shows each expert's value judgments on discounting parameters (rate of pure time preference; inequality aversion; n = 173). The triangle (1.5%; 1.45) indicates the choice of discount parameters by Nordhaus (2018a) and the blue square (0.5%; 1) the median expert's view on intergenerational welfare.* ***B-D*** *depict the 95 (grey-shaded area) and 66 (blue-shaded area) percentile ranges in terms of intergenerational fairness for three climate policy measures: the social cost of CO_2 (in US$ per ton), industrial emissions (in gigatons of CO_2) and global mean temperature increases from 1850-1900 levels (in degrees Celsius). These ranges do not correspond to confidence intervals relating to uncertainty about forecasts, rather they capture how the disagreement about discounting parameters affects the optimal paths when incorporated into our updated DICE model.* ***B-D*** *also compare climate policy pathways implied by Nordhaus' discounting in this updated DICE (black line) to those resulting from the median expert's view (blue line) and the median path (green line). While Nordhaus' discounting implies an optimal carbon price of $82 in 2020 in our updated DICE, the median expert path (view) translates into a value of $101 ($208) in 2020.*

It is important to recognize that with Nordhaus' discounting parameters we find a temperature increase of only 2.0°C in this updated DICE model instead of 3.5°C in the original DICE (Fig. 2D). The median expert view (median path) leads to an increase in temperature of 1.4°C (1.8°C) by 2100, with a 66 percentile range of 1.2-2.2°C. Overall, given the assumptions on the technological environment and climate constraints in the updated DICE, 32% of all model runs resulting from the expert views on discounting parameters would lead to an optimal policy that stays below 1.5°C in 2100, while 76% of all model runs stay below 2°C in 2100. These findings suggest that there is support for the Paris climate targets being "optimal" from a social welfare perspective.

Fig. 3 summarizes the consequences of each sequential model update reported in Fig. 2 on the optimal climate policy paths. Views on discounting parameters translate into optimal temperature change by 2100 (Fig. 3A), the timespan to full decarbonization (Fig. 3B), and the SCC in 2020 (Fig. 3C) for each considered sequential model update to DICE.

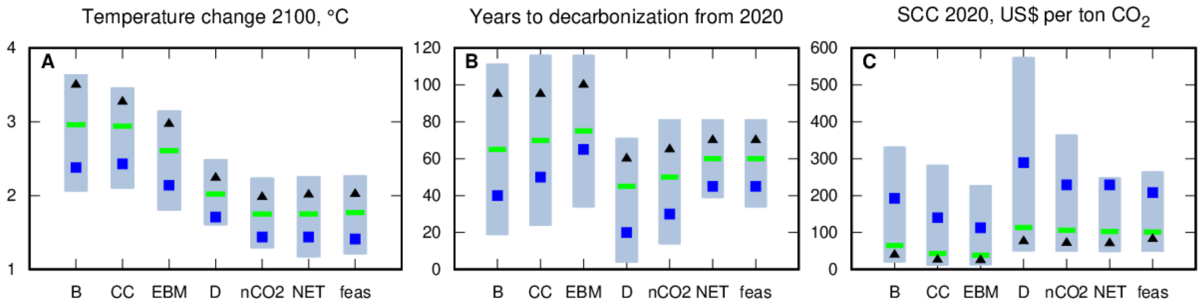

Figure 3. Effects of each sequential model update on optimal climate policy paths. *The 66 percentile range of expert's recommendations on the pure rate of time preference and inequality aversion translates into the optimal temperature change by 2100 from 1850-1900 levels (****A****), the years to decarbonization (****B****) and the social cost of carbon in 2020 (****C****) for each sequential update to DICE considered in this paper. Starting from the DICE 2016R2 baseline (B) we cumulatively add changes to*

the DICE model. First, we change the carbon cycle (CC), then add the energy balance model (EBM), third the temperature-damage relationship (D), fourth the exogenous path for non-CO_2 forcing (nCO2), fifth the availability of negative emissions technologies (NET) and finally we add the technologically feasible speed of decarbonisation (feas). For better visibility of the changes, we only depict the 66 percentile ranges based on the different expert views on discounting parameters in the boxplots (Extended Data Fig. 10 shows a box-and-whiskers plot with the 95 percentile ranges). The triangle indicates the optimal path that is consistent with the Nordhaus[34] choice of discount parameters, the blue square reflects the median expert's view on intergenerational welfare, and the green bar the median expert path.

Updating the carbon cycle model has mixed impacts on the temperature in 2100 depending on the combination of discounting parameters: it increases optimal warming for the median expert view and decreases it for Nordhaus' parameter choices. For most discounting parameter choices, the carbon cycle update reduces the SCC in 2020 and delays the date of decarbonization. Recalibrating the energy balance model reduces the optimal temperature increase by 2100 and prolongs the time until optimal decarbonization for all discounting parameter combinations. This reduces the cost of emitting an additional ton of CO_2 into the atmosphere for the current generation.

Updating economic damages increases the SCC in 2020, makes it optimal to decarbonize earlier, and results in a lower temperature change by 2100. Introducing a lower non-CO_2 forcing pathway leads to a further drop in optimal temperatures, increases the time to decarbonization and reduces the SCC in 2020. Allowing for the availability of net negative emissions from 2050 leads to postponing emission reductions. This is consistent with the literature on larger scale integrated assessment models[69].

In our model runs, negative emissions technologies shift the welfare costs of decarbonization to future generations while the associated temperature drop by 2100 is only minor. Adding the feasibility constraints leads to slight increases in the temperature in 2100 and the time until decarbonization, but it only has a small impact on the SCC.

Each of the individual updates that we make to DICE has different impacts on the optimal path. The largest impact on the optimal temperature in 2100 and the SCC in the year 2020 arises from the updates to the discounting parameters. The sensitivity to discounting assumptions exists irrespective of when they are introduced in the sequence of model updates, as is reflected in Fig. 3. The substantial vertical differences between the median experts' view and the Nordhaus choice at each cumulative update show how crucial it is to consider a more representative range of recommendations on intergenerational welfare to inform policy. In combination with discounting assumptions, updating damages also has a large effect on the SCC[78]. Specifically, updating the damage function more than doubles the SCC in 2020 to US$ 289 compared to the previous step of updating the energy balance model. This impact would be even more pronounced had we used the damage functions with higher damage exponents or overall higher damages[47,50,51,78] (see Methods and Fig. S3 in the additional Supplementary Information).

Finally, the carbon cycle and energy balance model, updated assumptions for non-CO_2 forcing, and negative emissions technologies each have two important effects on the optimal path. First, they contribute to a reduction in the optimal temperature. Second, they relax the pressure on current generations to rapidly decarbonize, thus postponing the date at which decarbonization occurs. This latter effect helps the economy to remain within a given temperature limit at lower welfare costs by allowing a smoother transition to decarbonization over time. These observations reflect well the way in which inter-temporal welfare trade-offs play out in economic appraisals of climate change. These two effects are also reflected in a SCC that falls with the carbon cycle and energy balance updates, and negative emissions technology, and rises with damage and social discounting updates.

Although we have made a number of modifications to DICE in this paper we have made a point of keeping the number of changes to a minimum. Indeed, there are many factors ignored in the analysis that should be part of a more comprehensive appraisal of climate policies. In addition to uncertainty, these include, tipping points, relative scarcity of non-market goods, climate-induced migration and consideration of a host of alternative ethical frameworks. In Box 2, we summarize a number of key limitations and potential extensions proposed in the literature. Likewise, an analysis of the political process of setting the UN climate targets themselves is outside the scope of this article.

Box 2: Limitations and extensions of DICE

Inequality and heterogeneity: A crucial assumption of DICE is the use of a representative agent that maximizes global well-being. Thus our analysis ignores crucial aspects of heterogeneity relating, among others, to regional and sub-regional differences in preferences, income levels, adaptive capacity and damages. Nordhaus early on developed a regionalized version of DICE, called RICE[79], which has subsequently been employed[80] and extended to a sub-regional level[81] to study the effect of inequality on climate policy measures. Furthermore, there are analytic models that deal with key heterogeneities[82].

Uncertainty: While DICE is a deterministic model, the long-term future is inherently uncertain. This relates to processes governing economic development[83] and discount rates[63,84] , as well as to climate dynamics and climate damages[12,14,15], including the location and extent of tipping points in coupled climate-society systems[85,86]. Thus, a more comprehensive economics assessment of climate change should consider various forms of uncertainty, ranging from standard risk to fundamental ignorance[87]. Besides applications of Monte-Carlo analyses in DICE[6,34], stochastic computational or dynamic programming applications[55,88,89], and analytic models[49,54,90] have already been employed.

Climate damages: DICE assumes a quadratic damage function of temperature increase on economic output, but a host of other functional forms of the damage function may be plausible. This includes variants with higher damage exponents, in line with the idea of potentially catastrophic climate damages[12.91], or empirically estimated damage functions[47] and expert survey evidence[49] that points towards higher overall damages. However, damages from climate change not only hit output but also affect the capital stock and thus growth directly[92-94]. Finally, a considerable share of damages will affect goods and services that are not traded on markets, such as environmental amenities, biodiversity and coral reefs[45] . These damages to non-market goods—and their associated relative price changes—should be explicitly modeled and can substantially impact optimal climate policy[16,17] .

Endogenous growth: DICE assumes an exogenous decline in technological progress, yet much of modern growth theory is concerned with endogenous channels of growth[95-99]. Furthermore, endogenous population change will likely not only impact resource demand but also affect innovation[100,101].

Abatement cost function: The abatement function in DICE is calibrated to smooth reduction rates. However, with faster rates of reduction, several non-equilibrium phenomena could make the reductions more costly, e.g., through increasing levels of unemployment in certain regions. In addition, if the global efforts to reduce emissions are poorly coordinated, as is the case now, with certain regions paying much higher attention to the problem, then costs might also be higher than what would be the case under perfect coordination[74,102]. On the other hand, scale effects and technical progress can considerably reduce abatement costs as witnessed in renewables such as solar and wind in recent years. Relatedly, the marginal abatement costs curve assumed in DICE could also be made endogenous, such as to feature learning-by-doing dynamics[103].

Alternative ethical frameworks: DICE builds on the standard consequentialist Discounted Utilitarian welfare function that still forms the workhorse model of the economic analysis of climate policy. However, the literature has proposed and applied numerous alternative ethical approaches[22,104] . Alternative welfare criteria include, among others, Sustainable Discounted Utilitarianism[105,106], Rank-Discounted Utilitarianism[107], and Prioritarianism[21].

Conclusion

We used recent findings from the literature to update several key parameters of the prominent DICE model developed by Nobel Laureate William Nordhaus. Our updated DICE model is in line with the higher Paris temperature target, with an optimal temperature increase of 2.0°C by 2100, even with Nordhaus' assumptions on discounting[1,34], and otherwise well below 2°C towards 1.5°C. Of course, the basic DICE model is deterministic. Under uncertainty, to ensure the maximum temperature increase is less than 2°C in 2100, or indeed to hit the lower 1.5°C UN Target, with any degree of certainty (e.g. in 95% of cases) would require more stringent mitigation policies than the central, deterministic case presented here.

Even if the UN Paris Agreement is attainable, intergenerationally fair and economically optimal in our updated version of DICE, it is also necessary to consider the political feasibility of meeting these stringent climate targets. One way to assess this is to investigate the level of the optimal price of CO_2 and the speed of decarbonization. The mitigation policies that can be pursued in practice are likely to be constrained in these dimensions, as recently witnessed in response to the imposition of carbon taxes in Canada and France in 2018-19. While the median expert path implies a carbon price of around US$ 100 in 2020 and zero emissions in

2080, the median expert's view results in an optimal CO_2 price of just above US$ 200 per ton in 2020 and complete global decarbonization by 2065. This contrasts with a carbon price of around US$80 that results from the discounting parameters of Nordhaus[1,34] in our updated model and a carbon price of around US$ 40 in Nordhaus' original DICE calibration. Thus, carbon prices resulting from the majority of expert views in our updated DICE model are considerably higher than what is being implemented in most sectors even in the most ambitious regions of the world. However, it is within the range of what is currently used in governmental guidance for Cost Benefit Analysis, such as in Germany where a SCC of around $200[108] is used, or implemented as actual or effective carbon taxes in certain sectors in many European countries such as the Netherlands, Sweden and Switzerland[109]. It should also be recognized that total current taxes on gasoline in Europe can amount to effective taxes that far exceed our two median cases, with more than $400 per ton of CO_2 in Germany, for instance[110]. Although they are not labelled carbon taxes, these policies provide some perspective on what could be possible.

Yet these countries are the exception and make up a small part of the global economy. Furthermore, while carbon pricing is key to achieving the range of optimal climate targets we present, there are major obstacles to such policy. First, there is lobbying by powerful and concentrated industries. Second, there is fear of reduced competitiveness. Naturally, this is mitigated if the policies are global but the fear nevertheless highlights a difficult issue of policy coordination between nations. A third obstacle is the perception that carbon taxes hurt the poor disproportionally[111]. It is often argued that distributional concerns are a chief source of resistance from significant shares of the electorate. Yet, the regressive nature of carbon taxes is often exaggerated and in fact, fuel taxes are often progressive in low-income countries where only the very richest have vehicles and air conditioning[112]. Yet distributional concerns may still be real in many contexts and considerable thought will have to go into the design and implementation of carbon pricing in order to mitigate these widely held political economy concerns[113,114]. Perhaps one of the chief obstacles to policy stems from a straightforward resistance to higher prices. In aviation, for instance, long-haul flights may double in price if a carbon tax of $300 per ton of CO_2 were levied.

The UN Paris Agreement is an expression of the international view that rapid action is necessary to limit the damages caused by climate change. The IPCC Special Report on the 1.5°C target[36] then illustrated the measures required to meet the agreed limit of 1.5°C. In this Analysis, we have shown that the benefits of limiting global warming to (well) below 2°C outweigh the costs of doing so when considering updates to the most standard and influential economic cost-benefit framework for climate change appraisal: Nordhaus' DICE model. Our results suggest that there is no inherent disparity between the UN climate targets and the principle of economic optimality. Nevertheless, enacting ambitious policies remains a key challenge.

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Author contributions

M.A.D., M.C.F., B.G., M.C.H. and F.N. conceived a study on DICE focusing on the role of discounting and the damage function which was merged with parallel work on the role of the carbon cycle, the energy balance model and non-CO_2 forcers in DICE developed by C.A. and D.J.A.J., at a workshop organized by T.S. in Gothenburg; M.C.H. performed the numerical modeling, data analysis and graphical representation of results with substantive input from D.J.A.J. and close feedback from M.A.D. and F.N.; the writing of the manuscript was led by M.A.D., B.G., M.C.H. and F.N. with significant input from all other authors.

Authors declare no competing interests.

Data Availability Statement

The data that support the plots within this paper and other findings of this study are available in the Source Data files.

Code Availability Statement

All code used in to produce the analysis is available at the following repository: https://www.openicpsr.org/openicpsr/project/119395/version/V1/view/ under a creative commons 4.0 license. Details of implementation can be found in the Supplementary Information files.

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Methods

The DICE 2016R2 model is presented in detail in Nordhaus[34]. We implement DICE with the AMPL optimization software and use the Knitro solver (version 10.2) to obtain the numerical dynamic optimization results presented in this paper. Note that since we use a different numerical optimization solver and modeling language than Nordhaus[34], our numerical results differ slightly. We provide the programming code and data in separate files. To ease comparability to Nordhaus'[1,34] figures, we present industrial emissions, the social cost of carbon and temperature increases only until the year 2100, while the optimization runs extend until 2500, as in DICE.

Here we provide a more detailed account of the calibration of the updated DICE model. We do so by first presenting results of the baseline DICE 2016R2 of Nordhaus[34]. In a second step we summarize the updates to key climate and economics-related functional forms and parameters leading to the final model specification presented in the main text. The resulting climate policy paths that we present in Fig. 2 of the main text are framed in terms of what is intergenerationally optimal as reflected by value judgments on the rate of pure time preference and inequality aversion. Thus, we also offer a more detailed perspective on the diverging views on discounting parameters, one of the key sensitivities in the economic analysis of climate change. As a third step we analyze how each of the updates subsequently affect climate policy paths for (i) Nordhaus' choice of discounting parameters, (ii) the median expert's choice of discounting parameters, (iii) the median path, and for the 95 and 66 percentile ranges resulting from different expert views on intergenerational optimality.

Nordhaus'[34] baseline calibration is the starting point of our analysis. The resulting pathway for the social cost of CO_2, starting at 39 US$ in 2020 and rising to 296 US$ per ton of CO_2, lies within the politically discussed range for carbon prices. Both the optimal date of decarbonization in the next century and the optimal atmospheric temperature change of 3.5°C by 2100, rising to 4°C in the middle of the next century are far outside climate policy pathways that are consistent with the UN temperature limits of 2°C and 1.5°C. We provide detailed results of Nordhaus'[34] baseline calibration in Fig. S1 of the additional Supporting Information.

We argue that the following adjustments from more recent climate and economics research closes the gap between Nordhaus' calibration of DICE2016R2 and the Paris Agreement.

Carbon cycle

Nordhaus[34] writes that the 2016 version of DICE *"incorporates new research on the carbon cycle. Earlier versions of the DICE model were calibrated to fit the short-run carbon cycle (primarily the first 100 years). Because the new model is in part designed to calculate long-run trends, such as the impacts on the melting of large ice sheets, it was decided to change the calibration to fit the atmospheric retention of* CO_2 *for periods up to 4,000 years. Based on* *studies of Archer et al.[115], the 2016 version of the three-box model does a much better job of simulating the long-run behavior of larger models with full ocean chemistry. This change has a major impact on the long-run carbon concentrations."* While this is an improvement over previous DICE versions, it does not take into account non-linearities in the carbon cycle. This is important since the fraction of a CO_2 emissions pulse that stays in the atmosphere at any point in time in the future depends on the past cumulative emissions of CO_2. Roughly the larger the cumulative emissions, the larger the fraction that remains[115-117]. Although Nordhaus does not explicitly describe which model experiment in Archer et al.[115] he uses for calibrating the box model in DICE, it appears from numerical comparison of the carbon cycle impulse response in DICE with those impulse responses presented in Archer et al.[115] that the calibration is based on an impulse size of 5000 GtC. That is roughly a factor five larger the amount of cumulative CO_2 emissions that are compatible with the targets in the Paris Agreement. Hence, given the non-linearities in the carbon cycle and climate carbon cycle feedbacks, the standard carbon cycle in DICE 2016R2 underestimates the removal of CO_2 from the atmosphere by the biosphere and ocean when assessing emission pathways with cumulative emissions considerably smaller than 5000 GtC. As a consequence of this, the concentration and thus also the temperature impact of each ton of CO_2 emitted is likely to be too high in DICE 2016R2 for cumulative emission levels compatible with a stabilization of global mean surface temperature well below 2°C.

In order to deal with these issues, we change the carbon cycle in DICE 2016R2 so that it takes into account the non-linearity in the carbon cycle as well as climate carbon cycle feedbacks. Specifically, the linearized carbon cycle representation in DICE is changed to the carbon cycle representation in the simple climate model FAIR[29,30], which was used to assess the climate impact of various emissions pathways in the IPCC[36] Special Report. This enables us to model a carbon cycle that is consistent with large scale carbon cycle models, such as those analyzed in Archer et al.[115], over a broad range of emission pathways, and not only pathways with emission levels far above those that are consistent with the Paris Agreement.

In the Extended Data Fig. 1, we compare the optimal paths for atmospheric carbon in the standard DICE2016R2 calibration to the updated carbon dynamics based on Nordhaus' standard discounting parameters.

Energy balance model

The temperature response to changes in radiative forcing in Nordhaus[34] is not consistent with the response in state-of-the-art climate system models[37]. Since the Energy Balance Model (EBM) in DICE is a two-box model it has two characteristic response time scales whose calibration are different than those presented in Geoffroy et al.[37]. The rapid response (yearly time scales related to the response of the well mixed upper ocean layer) is too slow in DICE2016R2, while the slow response (century time scales related to the response of the deep ocean) is too fast compared to advanced climate system models. The latter implies that for a given radiative forcing step change the equilibrium temperature level is approached too fast. We have therefore recalibrated the EBM so that its parameterization represents the average characteristics of climate models used in the Coupled Model Intercomparison Project Phase 5 (CMIP5)[37]. The equilibrium response, i.e. the climate sensitivity in DICE (being 3.1°C for a doubling in the CO_2 concentration), is left unchanged since it fits well in the middle of the likely distribution of Equilibrium Climate Sensitivity[5,39,40].

In the Extended Data Fig. 2, we compare the optimal temperature dynamics in DICE 2016R2 with the dynamics when only the new EBM climate system model (based on Geoffroy et al.[37]) is implemented. The optimal temperature drops by around half a degree Celsius due to the introduction of the EBM only. Additionally, our recalibrated model includes a higher initial temperature level in 2015 compared to the standard DICE 2016R2. That is for two reasons. First, in DICE2016R2 the reference period for the atmospheric temperature change is 1900 while the updated EBM uses the average between1850-1900 and hence, the temperature has increased slightly more since the 1850-1900 period. Second, we initialize the updated EBM with historical forcing estimates to ensure that the model's initial conditions in 2015 are internally consistent (i.e., the temperature in the two boxes are consistent with the radiative forcing history). We are not aware of any information on how this calibration is dealt with in the standard DICE 2016R2.

Economic damages from climate change

The climate damage function in DICE translates a temperature increase into a percentage change in global GDP. Due to the large uncertainty involved in estimation, meta-analyses are a standard tool to inform the choice of the parameter that scales the temperature-damage relationship in models such as DICE[28,43,44,46].

Tol[43] provided an influential meta-analysis of climate damages, which served as a basis for previous versions of the DICE model. Both the 2009 meta-analysis and an update, Tol[44], have been found to contain statistical errors[28]. As a result Nordhaus revised the climate damage function in the 2016 version of DICE[34,46] based on his own meta-analysis of 36 studies that report a damage estimate. Each of these estimates is treated as an independent draw from an underlying damage function. This is a precondition for using the usual statistical analysis needed. However, the independence assumption can be questioned as several of the estimates come from the same limited circle of authors. The selected climate damage function translates a temperature increase of 3°C into a damage of 2.12% of global GDP.

Howard and Sterner[28] provide an up-to-date meta-analysis of the temperature-damage relationship. They find strong evidence that Nordhaus and Moffat's[46] damage estimate is biased due to duplicates and omitted variables in the regression. In their preferred model[28] (Regression 4 in Table 2), total damages that include a markup of 25% for omitted non-market damages from climate change are substantially higher, reaching 6.69% of global GDP for a 3°C temperature increase. This is closer to recent empirical evidence[47], which shows that economic damages from climate change may be even more severe, but has the merit that it can be incorporated directly into the DICE model. Nordhaus[1] also used this damage function in sensitivity analysis. Extended Data Fig. 3 compares the baseline to the isolated effect of the updated optimal economic damage from climate change (as a percentage of global GDP) under Nordhaus' discounting choices. Damages are substantially higher in the updated model for most of the time horizons considered.

Intergenerational welfare

In the standard social objective function used in DICE, welfare weights across generations can be chosen based on both normative and positive considerations. Drupp et al.[24] have undertaken a large, representative survey of academics publishing in leading economics journals who have specific expertise on these matters to determine their views on the values that the welfare weights in the social objective function should take. 173 respondents provided complete responses on the normative parameters in DICE (See Box 1). In the main text, we employ two approaches to find some central, mediating value among the different expert opinions, for policy purposes. We now report the motivation behind these concepts of central tendency by explaining how the "median expert view" and "median expert path" are constructed.

The "median expert view" represents the median response of all 173 experts for each of the two discounting parameters, the rate of pure time preference and inequality aversion. The "median expert view" has a theoretical justification in the literature on voting outcomes. It can be interpreted as the voting outcome if experts have circular indifference curves around their central value, and vote simultaneously and separately over the two welfare parameters[59,60].

The "median expert path" represents the median of all model runs for the SCC, temperature and emissions associated with each of the 173 experts' chosen pair of discounting parameters at each point in time. The "median expert path" has a theoretical justification in the literature on voting outcomes. It can be interpreted as the voting outcome if experts have single-pealed preferences, and vote over a specific end point of a climate path at a given point in time[58], instead of parameters as in the case for the "median expert view". Hence, a given "median expert path" tracks voting outcomes for a given climate path at any given point in time.

The "median expert path" should primarily be viewed as a pragmatic, alternative definition of central tendency, as the superior mediating statistic it is not clear a priori. The "median expert path" offers mediating climate paths that are less stringent compared to the paths implied by the "median expert view".

It should be noted that a major finding of the expert survey is that a majority of experts do not follow the simple Discounted Utilitarian approach and associated Ramsey rule (See Box 1), but deviate for a number of reasons[24]. These include project risk, uncertainty, environmental scarcity, effects of inequalities within generations as well as alternative ethical approaches (See Box 2). As the mean (median) imputed simple Ramsey rule in the expert survey is higher than the recommended mean (median) social discount rate, these extensions are likely to lead to recommending more stringent climate policy. The main text may therefore depict conservative results.

Non-CO_2 forcing

Abatement of non-CO_2 emissions are critical when aiming for stringent climate stabilization levels[2,36]. The scenario assumption for the radiative forcing from non-CO_2 climate forcers in Nordhaus[34] is exogenously given. It is substantially higher compared to what is estimated in other climate scenario work analyzing pathways compatible with stabilization of global mean surface temperature around 1.5-3°C above the pre-industrial level, e.g., the Representative Concentration Pathways (RCP) 2.6 and 4.5[119] or the Shared Socioeconomic Pathways (SSP) towards 1.9 W/m^2 [118]. While several of these abatement options for non-CO_2 emissions might not be cost-effective at modest carbon prices as those suggested in the original DICE model (39 US$ in 2020), it very likely becomes cost effective to abate non-CO_2 greenhouse gases if governments implement policies that will meet current UN climate targets[2,120]. This implies that the exogenously set radiative forcing pathway for non-CO_2 emissions in DICE is too high for the majority of our optimal policy runs. We therefore consider a pathway of non-CO_2 greenhouse gases that is better aligned to the CO_2 price and temperature levels we obtain with the updated version of DICE. Specifically, we have changed the radiative forcing scenario from non-CO_2 forcers so that it matches the path of the REMIND integrated assessment model using the SSP2 scenario meeting a non-CO_2 forcing level of 2.6 W/m^2 in 2100[31]. This scenario reaches similar carbon concentrations, radiative forcing and temperature levels as obtained in our fully updated DICE model. In the Extended Data Fig. 4, we compare the standard to the updated path for non-CO_2 forcing in isolation.

Negative emissions technologies

A key difference between the DICE and the IPCC Special Report[36] is the stance regarding the availability of carbon removal technologies leading to net negative emissions. While the scenarios considered by the IPCC[2,36] make use of negative emission technologies roughly by the year 2050, the DICE 2016R2 model assumes that this will only be feasible from 2160 onwards. In line with the pathways assessed in the IPCC report, we allow for the possibility of negative emissions technologies from mid-century onwards. We set the upper level of abatement to 120% of baseline emissions as in DICE 2016R2. Consequently, emissions reach -18 $GtCO_2$ per year for the lower 95% bound of expert views on discounting by 2100. For comparison, the emission pathways that are assessed in IPCC SR 1.5 and that meet the 1.5°C level by 2100 have a median emission level of -12 $GtCO_2$ per year in 2100, with a 90% interval of -20 $GtCO_2$ per year to -2.3 $GtCO_2$ per year, while the emissions level in 2070 has a median of -8.0 $GtCO_2$ per year and a 90% interval of -15 $GtCO_2$ per year to -0.70 $GtCO_2$ per year (estimated from data available in IAMC 1.5°C scenario explorer[72]). The timing of the availability of negative emissions technologies as well as their potential magnitude are still intensely debated[69,70], and will ultimately, similar to all abatement technologies, depend on the interplay of technological development and (expected) carbon prices.

Feasibility constraints

We impose a set of constraints on the maximum rate of technologically feasible decarbonization. These conditions allow for a more credible study of low-emission scenarios. The main text contains all relevant information. In a next step, we present the resulting climate policy paths under updated model specifications. In Fig. S2 of the additional Supporting Information, we show how different positions on social discounting translate into plausible ranges of climate policy paths within the baseline DICE 2016R2 model calibration.

Optimal climate policy paths under updated model specifications

First, we now consider the introduction of the new carbon cycle dynamics. Extended Data Fig. 5 shows how different positions on social discounting translate into plausible ranges of climate policy paths in DICE 2016R with the new updated carbon cycle.

The maximum SCC in the 66 (95) percentile range are $277 ($1017) in the year 2020 and $1080 ($2310) in 2100. By contrast, the minimum SCC in 2020 in the 66 (95) percentile range is $16 ($3) increasing to $161 ($24) in 2100. Nordhaus' SCC is at $25 in 2020 and $245 in 2100. By contrast, the median expert view translates into a SCC of $140 in 2020, increasing to $742 in 2100. The median path in turn results in a SCC of $43 in 2020, increasing to $484 in 2100.

In the central 66 percentile plausible range, the decarbonization of the global economy occurs 5 years later compared to the baseline model; the economy should either be decarbonized in 2045 or 2135. In Nordhaus' best-guess, the economy would not be decarbonized within this century, while optimal decarbonization takes place by 2065 in the median expert's view. The median path in turn results in decarbonization by 2090.

While Nordhaus' view on social discounting translates into 3.27°C warming by 2100, the median expert view (median paths) leads to an increase in temperature of 2.43°C (2.93°C) by 2100. In the 66-percentile range, the temperature increase in 2100 is as high as 3.43°C (3.53°C) at the upper end, and 2.13°C (2.0°C) at the lower end. Moreover, none of the model runs that result from the expert views would lead to an optimal policy that stays within the 1.5°C limit of the Paris Agreement. Overall, only 6% of all model runs stay below 2°C by 2100.

Second, we add the updated energy balance model. Extended Data Fig. 6 shows how different positions on social discounting translate into plausible ranges of climate policy paths in DICE 2016R2 with updated carbon cycle and energy balance model.

Compared to the model that only incorporates the updated carbon cycle the SCC decrease in almost all model runs. The maximum SCC in the 66 (95) percentile range are $221 ($752) in the year 2020 and $887 ($1720) in 2100. By contrast, the minimum SCC in 2020 in the 95 (66) percentile range is $6 ($18) increasing to $41 ($161) in 2100. The SCC using the discounting parameters of Nordhaus remains at $25 in 2020 and increases to $245 in 2100. By contrast, the median expert view results in a SCC of $113 in 2020, increasing to $609 in 2100. The median path in turn leads to a SCC of $38 in 2020, increasing to $406 in 2100.

In the central 66 percentile plausible range, the economy should either be decarbonized in 2055 or 2190. In Nordhaus' best-guess, the economy would not be decarbonized within this century, while optimal decarbonization takes place by 2065 in the median expert's view. The median path in turn results in decarbonization by 2090. Hence, the introduction of the updated energy balance model shifts optimal decarbonization into the future.

While Nordhaus' view on social discounting now translates into 2.97°C warming by 2100, the median expert view (median paths) leads to an increase in temperature of 2.14°C (2.61°C) by 2100. In the 95% (66%) range, the temperature increase in 2100 is 3.27°C (3.12°C) at the upper end, and 1.63°C (1.83°C) at the lower end. Moreover, still none of the model runs that result from the expert views would lead to an optimal policy that stays within the 1.5°C limit of the Paris Agreement. Overall, now 23% of all model runs stay below 2°C by 2100.

Third, we add the updated temperature-damage relationship according to Howard and Sterner[28]. Extended Data Fig. 7 shows how different positions on social discounting translate into plausible ranges of climate policy paths in DICE 2016R2 with updated carbon cycle, energy balance model and temperature-damage relationship.

Compared to the model that incorporates the updated carbon cycle and energy balance model only, the SCC is, not surprisingly, increased quite markedly by the introduction of the new damage function. The maximum SCC in the 66 (95) percentile range are $568 ($2363) in the year 2020 and $2203 ($5345) in 2100. By contrast, the minimum SCC in 2020 in the 95 (66) percentile range is $19 ($56) increasing to $129 ($448) in 2100. Nordhaus' SCC is $76 in 2020 and increasing to $593 in 2100. By contrast, the median expert view leads to a SCC of $289 in 2020, increasing to $1464 in 2100. The median path in turn results in a SCC of $113 in 2020, increasing to $995 in 2100.

In the central 66 percentile plausible range, the economy should either be decarbonized in 2025 or 2090. In Nordhaus' best-guess, the economy would be decarbonized by 2080, while optimal decarbonization takes place by 2040 in the median expert's view. The median path in turn results in decarbonization by 2065. Hence, the introduction of the updated temperature-damage relationship means that optimal decarbonization occurs sooner.

While Nordhaus' view on social discounting now translates into 2.24°C warming by 2100, the median expert view (median paths) leads to an increase in temperature of 1.71°C (2.02°C) by 2100. In the 95 (66) percentile range, the temperature increase in 2100 is 2.97°C (2.46°C) at the upper end, and 1.63°C (1.63°C) at the lower end. Moreover, still none of the model runs that result from the expert views would lead to an optimal policy that stays within the 1.5°C limit of the Paris Agreement. However, with updated damage function, 57% of all model runs stay below 2°C by 2100.

Howard and Sterner[28] provide an update on how damage estimates are combined to calibrate the standard damage function, but abstract from "catastrophic" climate damages. In the following, we run the DICE model with updated carbon cycle and energy balance model with the Weitzman[50] damage function calibrated to incorporate damages of 2.9% (50%) in units of output for a temperature increase of 3°C (6°C). Fig. S3 in the additional Supporting Information shows how different positions on social discounting translate into plausible ranges of climate policy paths in DICE 2016R2 with updated carbon cycle, energy balance model and temperature-damage relationship as in Weitzman[50] . Overall, the results show much less stringent climate policy as compared to the case with the Howard and Sterner[28] damage function. This is because, for up to 3°C temperature increase, the Weitzman[50] damage function has a similar shape as compared to the Nordhaus[34] damage function. Only for higher temperature increases, the "catastrophic" damages kick in, leading to 50% output loss for 6°C warming. Thus, in the relevant range of climate policy measures that are optimal according to DICE with updates carbon cycle and energy balance model (for example 3.27°C temperature increase by 2100 at the upper 95% bound), the "catastrophic" part of Weitzman's[50] damage function does not become relevant.

Fourth, we add the updated exogenous path for non-CO_2 forcing. Extended Data Fig. 8 shows how different positions on social discounting translate into plausible ranges of climate policy paths in DICE 2016R2 with updated carbon cycle, energy balance model, temperature-damage relationship and non-CO_2 forcing.

The updated non-CO_2 forcing scenario reflects an improved management of non-CO_2 emissions in line with the SCC and temperature levels we got after having updated the damage function. The maximum SCC values thus decrease; in the 66 (95) percentile range they are $358 ($1059) in the year 2020 and $1258 ($2193) in 2100. By contrast, the minimum SCC in 2020 in the 95 (66) percentile range is $19 ($54) increasing to $121 ($377) in 2100. Nordhaus' SCC is $72 in 2020 and increasing to $491 in 2100. By contrast, the median expert view leads to a SCC of $229 in 2020, increasing to $1006 in 2100. The median path in turn results in a SCC of $106 in 2020, increasing to $761 in 2100.

In the central 66 percentile plausible range, the economy should either be decarbonized in 2035 or 2100. In Nordhaus' best-guess, the economy would be decarbonized in 2085, while optimal decarbonization takes place by 2050 in the median expert's view. The median path in turn results in decarbonization by 2070.

While Nordhaus' view on social discounting now for the first time translates into staying below the 2°C temperature target (1.98°C warming by 2100), the median expert view (median paths) leads to an increase in temperature of 1.44°C (1.75°C) by 2100. In the 95 (66) percentile range, the temperature increase in 2100 is 2.68°C (2.21°C) at the upper end, and 1.28°C

(1.32°C) at the lower end. For the first time the 1.5°C temperature target by 2100 is in line with optimal economic policy according to a third of the 173 expert views on social discounting. Three quarters of all model runs stay below 2°C by 2100.

Fifth, we make negative emissions technologies available in 2050 instead of 2160 in DICE2016R2. Extended Data Fig. 9 shows how different positions on social discounting translate into plausible ranges of climate policy paths in DICE 2016R2 with updated carbon cycle, energy balance model, temperature-damage relationship, non-CO_2 forcing and negative emissions technologies available by 2050.

The earlier availability of negative emissions technologies increases the emissions budget in line with any given temperature target. The maximum SCC values in the 66 (95) percentile range are $242 ($425) in the year 2020 and $630 ($640) in 2100. By contrast, the minimum SCC in 2020 in the 95 (66) percentile range is $19 ($54) increasing to $113 ($362) in 2100. Nordhaus' SCC is $70 in 2020 and increasing to $446 in 2100. The median expert view leads to a SCC of $199 in 2020, increasing to $575 in 2100. The median path in turn results in a SCC of $103 in 2020, increasing to $569 in 2100.

In the central 66 percentile plausible range, the economy should either be decarbonized in 2060 or 2100. In Nordhaus' best-guess, the economy would be decarbonized in 2090, while optimal decarbonization takes place by 2070 in the median expert's view. The median path in turn results in decarbonization by 2080.

While Nordhaus' view on social discounting translates into 2.01°C warming by 2100, the median expert view (median paths) leads to an increase in temperature of 1.38°C (1.75°C) by 2100. In the 95 (66) percentile range, the temperature increase in 2100 is 2.63°C (2.23°C) at the upper end, and 0.90°C (1.20°C) at the lower end. 38% of all model runs stay within the 1.5°C limit of the Paris Agreement and 76% of all model runs stay below 2°C by 2100.

As the last step, we add the described technology inertia constraints resulting in Figure 2 in the main text.

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