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1 **Climate economics support for the UN climate targets**

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3 Mark C. Freeman⁶, Ben Groom^{7,*} & Thomas Sterner⁸

4

5 Abstract

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

18

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20 Limiting global warming to well below 2°C (let alone 1.5°C) as decided in the UNFCCC Paris
21 Climate Agreement is either unattainable or far from the economic optimal according to
22 William Nordhaus¹. Instead, his economic analysis implies a climate policy path that limits
23 global warming to 3.5°C by the end of the century and decarbonizes the economy only in
24 the next century. According to Nordhaus, this reflects the economically optimal balance
25 between future benefits and current costs. So while both the UN climate targets and Nobel
26 Prize winner highlight the need for a policy response to global climate change, they are
27 strikingly different in the stringency of the recommended temperature goals and the
28 implied emission pathways over the century^{2,3}.

29 Nordhaus' recommendations are derived from the DICE integrated assessment model (IAM),
30 which he created and developed in several steps^{4,5}. The model seeks to find the optimal
31 emission, temperature and carbon tax trajectories by balancing the costs of emissions
32 reductions and the damages of climate change, measured in economic terms. Emissions
33 reductions are justified provided the benefits of avoiding climate damages outweigh the
34 costs, e.g. higher costs associated with energy supply. Nordhaus was early in making his
35 model readily available to the research community and it has become central in climate
36 economic analysis and highly influential in policy discussions⁶⁻⁸. However, DICE has also been
37 criticized on a number of grounds. These include the choice of discounting parameters⁹⁻¹¹,
38 the model's omission of uncertainty and the risk for climate catastrophes¹²⁻¹⁵, the treatment
39 of non-market damages^{16,17}, and details of its climate model¹⁸⁻²⁰. Notably DICE's concept of
40 economic optimality, i.e. maximizing a Discounted Utilitarian social welfare function, has
41 been criticized for not reflecting the structure of optimal-control models that incorporate
42 risk and uncertainty¹⁵, and for its reliance on a single conception of intergenerational
43 welfare²¹⁻²⁴. DICE has also been subject to general criticism regarding the use of cost-benefit
44 analysis for climate policy purposes²⁵⁻²⁷.

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

54 Specifically, our updates to the basic DICE parameters draw from the latest findings on
55 economic damage functions²⁸, which Nordhaus¹ includes in a sensitivity analysis, together
56 with some of the latest climate science^{29,30}, and a broad range of expert recommendations
57 on social discount rates²⁴. This is complemented by revised assumptions regarding non-CO₂
58 greenhouse gas emissions³¹, the feasibility of negative emission technologies^{2,32}, and

59 constraints on the feasible speed of decarbonization^{2,33}. While some of these individual
60 updates have already been analyzed in the existing literature, our innovation is to analyze
61 their joint effect in DICE. This reveals that there is no inherent discrepancy between the
62 method underpinning the 2018 Economics Nobel Prize and the UN climate targets.

63

64 Updates to the Climate Module

65 Our first major update of the DICE model serves to better reflect the relationship between
66 emissions, concentration and temperature change. The climate module in the most recently
67 available version of DICE-2016R2³⁴ has two key limitations. First, DICE uses a linearized
68 carbon cycle model. This linearization has been undertaken for cumulative CO₂ emission
69 levels far higher than those compatible with the UN climate targets⁵. Consequently, the
70 impact on CO₂ concentrations of each emissions pulse is overestimated for any scenario in
71 which cumulative emissions are smaller than those found Nordhaus' optimal analyses^{34,35}.
72 Second, the energy balance model that is used to calculate the temperature impacts of
73 radiative forcing in DICE is not in line with the most recent advanced climate system models.

74 We first update DICE by implementing the carbon cycle module from the simple climate
75 model FAIR^{29,30}. This module takes into account how the removal rate of atmospheric CO₂
76 depends on past cumulative CO₂ emissions and changes in the global mean surface
77 temperature. The FAIR model was central for the assessment of emission pathways in the
78 IPCC Special Report³⁶ on 1.5°C warming².

79 To further improve the energy balance model in DICE, we recalibrate it so that its response
80 approximates the results of advanced climate system models included in the Coupled Model
81 Inter-comparison Project 5 (CMIP5)³⁷. The findings of CMIP5 were central for the climate
82 system model characterizations in the IPCC's Fifth Assessment Report³⁸. Geoffroy et al.³⁷ fit
83 simple two-box energy balance models to larger climate system models and show that these
84 simple models capture the global aggregated temperature dynamics of the large-scale
85 climate system models. We use the findings of Geoffroy et al.³⁷ to recalibrate the two-box
86 energy balance model in DICE and thus make its temperature dynamics consistent with
87 recent climate science.

88 The climate sensitivity that determines the equilibrium temperature change for a given
89 change in radiative forcing in DICE is set to 3.1°C for a doubling of the atmospheric CO₂
90 level⁵. As this remains consistent with the most recent central estimates of equilibrium
91 climate sensitivity^{39,40}, we leave it unchanged.

92 These updates roughly align our temperature pathways for a given emission scenario with
93 median estimates generated by simple climate models (FAIR and MAGICC) used in the IPCC
94 Special Report on 1.5°C warming^{2,41} and in the UN Emissions Gap Report³. See Methods and
95 Extended Data Fig. 1, 2, 5 and 6 for how the carbon cycle and EBM updates, respectively,
96 affect the optimal pathways. With these changes, lower temperature scenarios become

97 attainable, and the optimal temperature change by 2100 drops by half a degree compared
98 to the original DICE calibration, to just below 3°C by the end of this century.

99

100 Updates to the Economics

101 The optimal policy response in DICE is notoriously sensitive to two socio-economic inputs:
102 the social discount rate and the magnitude of economic damages incurred as temperatures
103 increase. The damage function has proven difficult to estimate because of the joint
104 uncertainties of physical climatic effects, the likely socio-economic responses to these
105 effects, and the economic valuation of these damages. Since the first attempts to estimate
106 economic damages for different temperature levels^{4,9,42-44}, methodologies have improved,
107 but key challenges remain⁴⁵. For instance, the quadratic damage function used in the
108 standard DICE is calibrated to a meta-analysis⁴⁶ that has been shown to suffer from multiple
109 citation bias, a form of non-independence²⁸. We instead use the damage function of
110 Howard and Sterner²⁸, who provide an up-to-date meta-analysis of the quadratic
111 temperature-damage relationship that corrects for the problem of non-independence. In
112 what they refer to as their “preferred model”, damages are substantially higher than in the
113 original DICE model, reaching 6.7% of global GDP for a 3°C temperature increase, as
114 compared to 2.1% in the standard DICE³⁴. This updated damage function is closer to, yet still
115 more conservative than, recent micro-econometric studies⁴⁷ and expert elicitations on the
116 topic^{48,49}, which estimate damages upwards of around 10% of global GDP for a 3°C
117 temperature increase. In our central model, we do not change the functional form of the
118 damage function, as in Weitzman^{12,50} or Glanemann et al.⁵¹, who apply the damage function
119 of Burke et al.⁴⁷, but rather update how damage estimates are combined to calibrate the
120 standard DICE damage function. When using our updated damage function alongside the
121 improved calibration of the carbon cycle and energy balance model, leaving DICE otherwise
122 unchanged, optimal temperature is reduced by a further 0.8 degrees to 2.2°C by 2100. For
123 robustness, we also undertake a simulation of the Weitzman⁵⁰ damage function, which has
124 higher order polynomial terms. The details of how this recalibration affects the model
125 results can be found in the Methods and Fig. S3 in the additional Supplementary
126 Information.

127 Next, we consider the determinants of intergenerational welfare as embodied in the social
128 discount rate (SDR). The SDR captures the ethical choices involved when policies transfer
129 well-being between current and future generations^{11,52,53}. The SDR can be simultaneously
130 viewed as embodying conditions on fairness and economic efficiency across generations.
131 Again, we do not change the structure of the DICE model, and our updates calibrate
132 parameters of the standard Discounted Utilitarian social welfare function used in DICE: the
133 pure rate of time preference and the elasticity of marginal utility (See Box 1). Other studies
134 have changed the structure of the social welfare function by separating out the coefficient
135 of risk aversion and the elasticity of intertemporal substitution, for instance. Indeed, there
136 are many different ways in which social welfare could be measured²⁴. Box 1 presents further

137 details on DICE's Discounted Utilitarian social welfare function, including extensions that
138 incorporate risk and uncertainty^{15,54-56}.

139 Climate policy recommendations are very sensitive to the choice of discount rate. Subjective
140 ethical perspectives underpin often irreducible differences of opinion on the matter, making
141 the choice of SDR the subject of disagreement. To inform policy it is therefore important to
142 understand the extent of disagreement. For this reason, we update the DICE model by using
143 the latest evidence on expert recommendations on the SDR. Drupp et al.²⁴ surveyed 173
144 experts on what Nordhaus⁵⁷ referred to as the two "central normative parameters" that
145 determine the SDR: the pure rate of time preference and elasticity of marginal utility. The
146 survey responses contain both positive and normative viewpoints on these parameters. By
147 using these data, we move away from the simple black and white characterization of social
148 discounting that is usually framed in terms of the Stern versus Nordhaus debate, and engage
149 with the full range of expert recommendations.

150 We employ two approaches to summarizing the range of expert recommendations for
151 policy purposes. First, we consider the climate paths associated with each expert's chosen
152 pair of discounting parameters and take the median ("median expert path") of all 173 model
153 runs for the SCC, temperature and emissions at each point in time. Second, we consider the
154 median response for each of the two discounting parameters separately ("median expert
155 view"). Both approaches have a theoretical justification in the literature on voting outcomes
156 (see Methods), and hence imagine a voting solution to the disagreement on the SDR⁵⁸⁻⁶⁰.

157 Both approaches place greater weight on future generations' well-being compared to
158 Nordhaus' calibration, leading to more stringent climate policies. Compared to the original
159 DICE using Nordhaus' discounting parameters, the optimal temperature is reduced by 0.5°C
160 and 1.1°C according to the "median expert path" and the "median expert view"
161 respectively. When combined with the previous updates to the climate science and the
162 damage function, the optimal temperature increase above the pre-industrial level falls from
163 2.2°C by 2100 in the case of Nordhaus' discounting parameter choices, to 2.0°C under the
164 "median expert path". The temperature change under the "median expert view" is even
165 lower at 1.7°C.

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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 $\eta\%$ 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:

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

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 ($\delta = 0\%$). Others have argued for positive values to account for the small risk of humankind’s extinction (e.g. $\delta = 0.1\%$)¹¹, because non-discrimination may demand unacceptably high saving from the current generation⁶¹, or because impatience is reflected in real rates of return on capital markets⁵².

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 $\eta = 1$ (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 decisions⁶². 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 IPCC³⁸. However, the rule has various extensions that experts recommend²⁴. 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.

173

174 Further updates

175 We next make two further changes to align DICE with the larger scale models used to
176 develop emission pathways that are assessed in terms of their likelihood to meet the 1.5°C
177 and 2°C limits in the recent IPCC Special Report on 1.5°C².

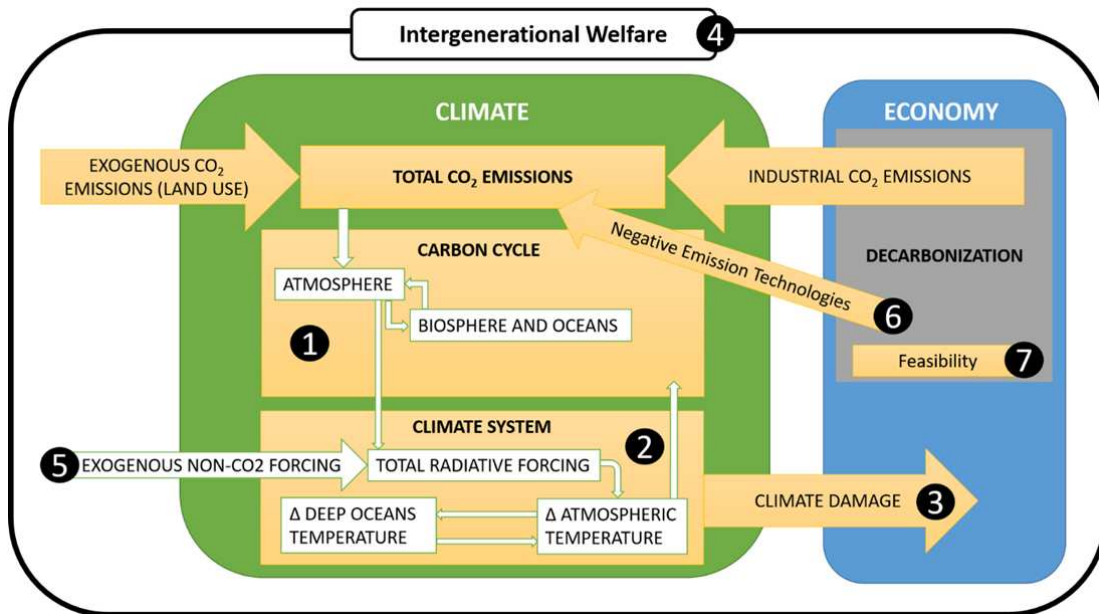
178 First, the original DICE model assumes an exogenous radiative forcing for non-CO₂. This
179 pathway for the non-CO₂ emissions is high compared to those generated by technology-rich
180 IAMs reaching temperature targets in line with those in the Paris agreement⁶⁵. We adjust
181 DICE by taking the pathway for non-CO₂ forcings estimated by the REMIND integrated
182 assessment model using the central Shared Socioeconomic Pathway (SSP2) that meets a
183 radiative forcing level of 2.6 W/m² in 2100³¹. This higher abatement of non-CO₂ greenhouse
184 gases makes even lower temperatures attainable. Among these paths we show that
185 Nordhaus' view on discounting yields (using the updated DICE model) an optimal
186 temperature increase of 2.0°C by 2100, and that reaching the 1.5°C climate target in 2100
187 (with some temporary overshoot) would be optimal according to the median expert's view.
188 In contrast, the median expert path would imply global warming of 1.8°C by 2100.

189 Second, we consider the role of negative emission technologies (NET). Nordhaus³⁴ only
190 allows for net-negative CO₂ emissions after 2160, while Nordhaus¹ allows for the possibility
191 of NETs within this century. Removing CO₂ from the atmosphere by Carbon Dioxide Removal
192 technologies such as Biomass Energy with Carbon Capture and Storage (BECCS),
193 afforestation, and Direct Air Capture have been suggested as a possible critical and cost-
194 effective abatement option to limit climate change^{2,35,66-68}. The timing of the availability of
195 negative emissions technologies and their potential magnitude are under debate^{69,70}, as well
196 as their relation to the use of different discount rates⁷¹. Although we are aware of
197 biophysical and socio-economic limits to all individual NETs, here we assume NET potentials
198 by 2050 in line with the recent literature^{36,69}. Feasibility will largely depend on reliable
199 institutions, good governance and structured incentives across the innovation cycle as well
200 as the implementation of a NET portfolio that overcomes the risk of relying on a single NET
201 like BECCS^{32,69}. The majority of emission pathways that stay below 2°C warming in the
202 Working Group 3 of IPCC's Fifth Assessment Report^{32,33} and the recent IPCC Special Report²
203 have net negative CO₂ emissions during the second half of this century. We allow
204 abatement of CO₂ to be at most 120% of the baseline emissions, as assumed by Nordhaus³⁴,
205 but allow for the possibility of net negative CO₂ emissions from mid-century onwards
206 instead of from next mid-century. This update results in optimal negative emissions of 18
207 GtCO₂ per year in 2100 at the lower 95% bound of expert recommendations on the social
208 discount rate. The emission pathways that are assessed in the IPCC Special Report and that
209 meet the 1.5°C level by 2100 have a median emission level of -12 GtCO₂ in 2100, with a
210 lower 90% bound of -20 GtCO₂ per year as estimated from data available in the Integrated
211 Assessment Modelling Consortium (IAMC) 1.5°C scenario explorer⁷². Allowing for NETs from

212 2050 lowers optimal temperatures but when introduced on top of our previously described
 213 changes to DICE, the effect on our two central runs is small: less than 0.1°C for both the
 214 median expert view and path.

215 Finally, DICE does not include constraints on the speed of emission reductions. Under
 216 Nordhaus³⁴ calibration this is not a concern since emission reductions occur relatively
 217 gradually. However, in our updated version of DICE, the optimal policy path displays very
 218 fast rates of emission reductions. Yet, there are practical limitations on how rapidly a
 219 transition to a decarbonized world economy can be implemented⁷³. Typically, these
 220 restrictions are incorporated into an integrated assessment model either by imposing a cost
 221 on the adjustment pace⁷⁴, or by technology inertia constraints⁷⁵. We impose a set of
 222 constraints on the maximum rate of decarbonization. First, we set the starting emissions to
 223 2020 levels. We also constrain the increase in emissions reductions between 2020 and 2045
 224 to no more than 2 GtCO₂ per year. This constraint is consistent with the upper range of
 225 emission reductions used for assessing the 1.5°C and 2°C limits in Clarke et al.³³ and Rogelj
 226 et al.². Finally, to avoid unrealistic emission reduction jumps for the period when negative
 227 emissions are feasible (2050 onwards), we limit the growth rate of the emissions reduction
 228 to 10% of the previous (5 year) period’s emissions reduction. Fig. 1 summarizes the
 229 sequential updates within a schematic structure of the DICE integrated assessment model.

230



231

232 **Figure 1. Updates to the climate-economy DICE model.** A stylized schematic of the DICE integrated
 233 assessment model that highlights the seven updates we make to the standard DICE version
 234 (2016R2³⁴). These are: (1) A carbon cycle based on the FAIR model^{29,30}, (2) an update of the energy
 235 balance model³⁷, (3) a revised economic damage estimate²⁸, (4) a range of expert views on
 236 intergenerational welfare²⁴, (5) non-CO₂ forcing in line with lower emission pathways³¹, (6) the
 237 earlier availability of negative emission technologies², and (7) constraints on the maximum rate of

238 *decarbonization*^{2,33}.

239

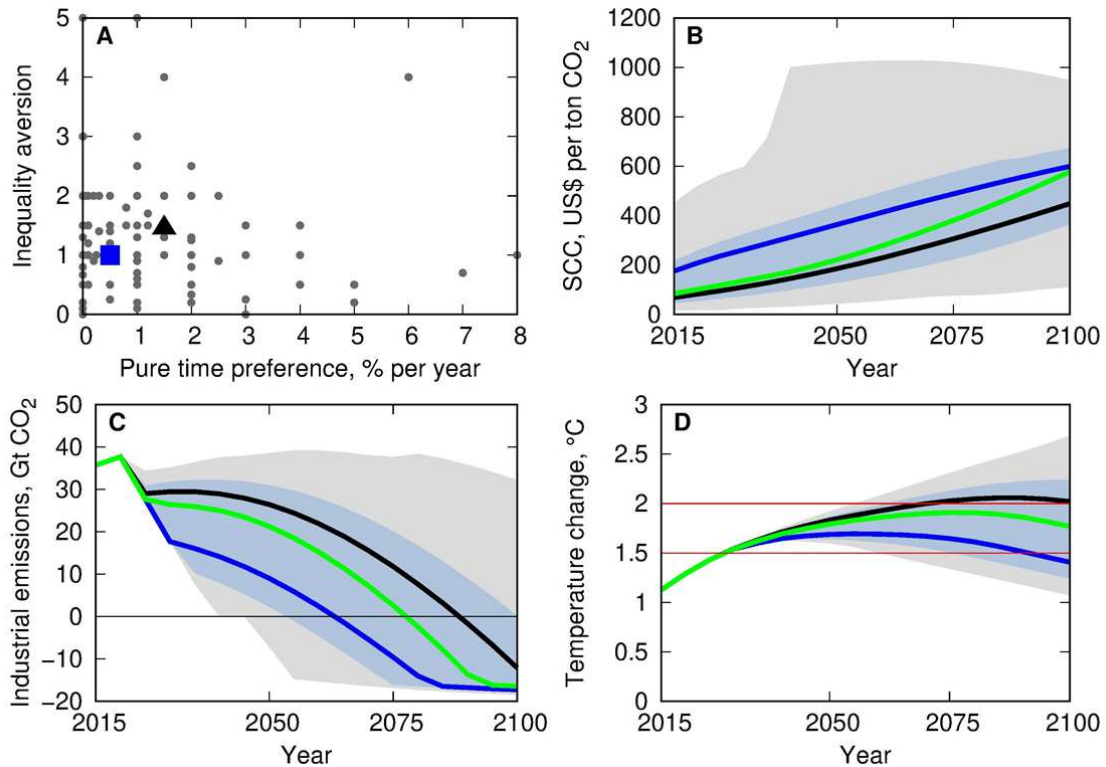
240 A central ground for climate policy

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

247 When expert views of the rate of pure time preference and inequality aversion²⁴ (Fig. 2A)
248 are translated into global social cost of CO₂ emissions (SCC) in US\$ per ton of CO₂ (Fig. 2B),
249 the highest SCC for 2020 in the 95 percentile range is \$520. By contrast, the lowest SCC in
250 the 95-percentile range is \$17. Nordhaus' discounting parameters imply a SCC of \$82 in
251 2020 in our updated DICE, which compares to a SCC of \$39 in the original DICE (see Fig. S1B
252 in the additional Supplementary Information). By contrast, the median expert view
253 translates into a SCC of \$208. The median path in turn results in a SCC of \$101. In sum, the
254 social cost of carbon is at least twice as high as in the original DICE calibration.

255 There is a substantial range of resulting pathways of global fossil fuels related CO₂ emissions
256 per year (Fig. 2C). In the central 66% range, the economy is decarbonized between 2055 and
257 2100. Given Nordhaus' choice of discounting parameters, the economy would be
258 decarbonized within this century, by 2090, while optimal decarbonization takes place by
259 2065 with the median expert's view. The median path in turn results in decarbonization by
260 2080.

261



262

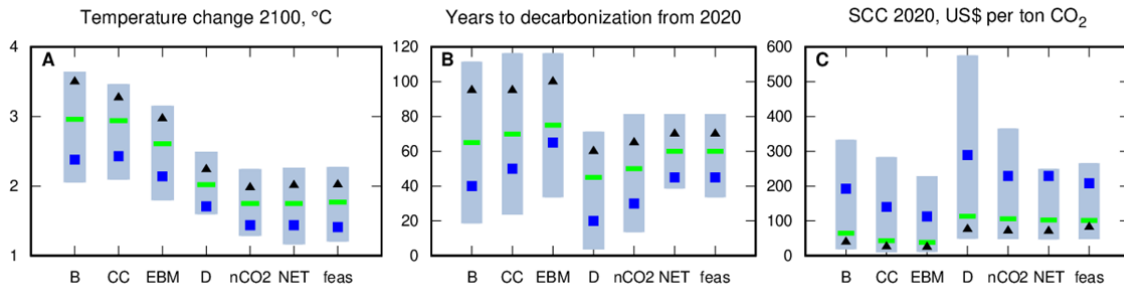
263 **Figure 2. Climate policy pathways in the updated climate-economy model DICE.** A shows each
 264 expert's value judgments on discounting parameters (rate of pure time preference; inequality
 265 aversion; $n = 173$). The triangle (1.5%; 1.45) indicates the choice of discount parameters by Nordhaus
 266 (2018a) and the blue square (0.5%; 1) the median expert's view on intergenerational welfare. B-D
 267 depict the 95 (grey-shaded area) and 66 (blue-shaded area) percentile ranges in terms of
 268 intergenerational fairness for three climate policy measures: the social cost of CO₂ (in US\$ per ton),
 269 industrial emissions (in gigatons of CO₂) and global mean temperature increases from 1850-1900
 270 levels (in degrees Celsius). These ranges do not correspond to confidence intervals relating to
 271 uncertainty about forecasts, rather they capture how the disagreement about discounting
 272 parameters affects the optimal paths when incorporated into our updated DICE model. B-D also
 273 compare climate policy pathways implied by Nordhaus' discounting in this updated DICE (black line)
 274 to those resulting from the median expert's view (blue line) and the median path (green line). While
 275 Nordhaus' discounting implies an optimal carbon price of \$82 in 2020 in our updated DICE, the
 276 median expert path (view) translates into a value of \$101 (\$208) in 2020.

277

278 It is important to recognize that with Nordhaus' discounting parameters we find a
 279 temperature increase of only 2.0°C in this updated DICE model instead of 3.5°C in the
 280 original DICE (Fig. 2D). The median expert view (median path) leads to an increase in
 281 temperature of 1.4°C (1.8°C) by 2100, with a 66 percentile range of 1.2-2.2°C. Overall, given
 282 the assumptions on the technological environment and climate constraints in the updated
 283 DICE, 32% of all model runs resulting from the expert views on discounting parameters
 284 would lead to an optimal policy that stays below 1.5°C in 2100, while 76% of all model runs

285 stay below 2°C in 2100. These findings suggest that there is support for the Paris climate
 286 targets being “optimal” from a social welfare perspective.

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



291

292 **Figure 3. Effects of each sequential model update on optimal climate policy paths.** The 66
 293 percentile range of expert’s recommendations on the pure rate of time preference and inequality
 294 aversion translates into the optimal temperature change by 2100 from 1850-1900 levels (A), the
 295 years to decarbonization (B) and the social cost of carbon in 2020 (C) for each sequential update to
 296 DICE considered in this paper. Starting from the DICE 2016R2 baseline (B) we cumulatively add
 297 changes to the DICE model. First, we change the carbon cycle (CC), then add the energy balance
 298 model (EBM), third the temperature-damage relationship (D), fourth the exogenous path for non-CO₂
 299 forcing (nCO2), fifth the availability of negative emissions technologies (NET) and finally we add the
 300 technologically feasible speed of decarbonisation (feas). For better visibility of the changes, we only
 301 depict the 66 percentile ranges based on the different expert views on discounting parameters in the
 302 boxplots (Extended Data Fig. 10 shows a box-and-whiskers plot with the 95 percentile ranges). The
 303 triangle indicates the optimal path that is consistent with the Nordhaus³⁴ choice of discount
 304 parameters, the blue square reflects the median expert’s view on intergenerational welfare, and the
 305 green bar the median expert path.

306

307 Updating the carbon cycle model has mixed impacts on the temperature in 2100 depending
 308 on the combination of discounting parameters: it increases optimal warming for the median
 309 expert view and decreases it for Nordhaus’ parameter choices. For most discounting
 310 parameter choices, the carbon cycle update reduces the SCC in 2020 and delays the date of
 311 decarbonization. Recalibrating the energy balance model reduces the optimal temperature
 312 increase by 2100 and prolongs the time until optimal decarbonization for all discounting
 313 parameter combinations. This reduces the cost of emitting an additional ton of CO₂ into the
 314 atmosphere for the current generation.

315 Updating economic damages increases the SCC in 2020, makes it optimal to decarbonize
 316 earlier, and results in a lower temperature change by 2100. Introducing a lower non-CO₂
 317 forcing pathway leads to a further drop in optimal temperatures, increases the time to

318 decarbonization and reduces the SCC in 2020. Allowing for the availability of net negative
319 emissions from 2050 leads to postponing emission reductions. This is consistent with the
320 literature on larger scale integrated assessment models⁶⁹.

321 In our model runs, negative emissions technologies shift the welfare costs of
322 decarbonization to future generations while the associated temperature drop by 2100 is
323 only minor. Adding the feasibility constraints leads to slight increases in the temperature in
324 2100 and the time until decarbonization, but it only has a small impact on the SCC.

325 Each of the individual updates that we make to DICE has different impacts on the optimal
326 path. The largest impact on the optimal temperature in 2100 and the SCC in the year 2020
327 arises from the updates to the discounting parameters. The sensitivity to discounting
328 assumptions exists irrespective of when they are introduced in the sequence of model
329 updates, as is reflected in Fig. 3. The substantial vertical differences between the median
330 experts' view and the Nordhaus choice at each cumulative update show how crucial it is to
331 consider a more representative range of recommendations on intergenerational welfare to
332 inform policy. In combination with discounting assumptions, updating damages also has a
333 large effect on the SCC⁷⁸. Specifically, updating the damage function more than doubles the
334 SCC in 2020 to US\$ 289 compared to the previous step of updating the energy balance
335 model. This impact would be even more pronounced had we used the damage functions
336 with higher damage exponents or overall higher damages^{47,50,51,78} (see Methods and Fig. S3
337 in the additional Supplementary Information).

338 Finally, the carbon cycle and energy balance model, updated assumptions for non-CO₂
339 forcing, and negative emissions technologies each have two important effects on the
340 optimal path. First, they contribute to a reduction in the optimal temperature. Second, they
341 relax the pressure on current generations to rapidly decarbonize, thus postponing the date
342 at which decarbonization occurs. This latter effect helps the economy to remain within a
343 given temperature limit at lower welfare costs by allowing a smoother transition to
344 decarbonization over time. These observations reflect well the way in which inter-temporal
345 welfare trade-offs play out in economic appraisals of climate change. These two effects are
346 also reflected in a SCC that falls with the carbon cycle and energy balance updates, and
347 negative emissions technology, and rises with damage and social discounting updates.

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

356

357 **Box 2: Limitations and extensions of DICE**

358 **Inequality and heterogeneity:** A crucial assumption of DICE is the use of a representative agent that
359 maximizes global well-being. Thus our analysis ignores crucial aspects of heterogeneity relating,
360 among others, to regional and sub-regional differences in preferences, income levels, adaptive
361 capacity and damages. Nordhaus early on developed a regionalized version of DICE, called RICE⁷⁹,
362 which has subsequently been employed⁸⁰ and extended to a sub-regional level⁸¹ to study the effect
363 of inequality on climate policy measures. Furthermore, there are analytic models that deal with key
364 heterogeneities⁸².

365 **Uncertainty:** While DICE is a deterministic model, the long-term future is inherently uncertain. This
366 relates to processes governing economic development⁸³ and discount rates^{63,84}, as well as to climate
367 dynamics and climate damages^{12,14,15}, including the location and extent of tipping points in coupled
368 climate-society systems^{85,86}. Thus, a more comprehensive economics assessment of climate change
369 should consider various forms of uncertainty, ranging from standard risk to fundamental
370 ignorance⁸⁷. Besides applications of Monte-Carlo analyses in DICE^{6,34}, stochastic computational or
371 dynamic programming applications^{55,88,89}, and analytic models^{49,54,90} have already been employed.

372 **Climate damages:** DICE assumes a quadratic damage function of temperature increase on economic
373 output, but a host of other functional forms of the damage function may be plausible. This includes
374 variants with higher damage exponents, in line with the idea of potentially catastrophic climate
375 damages^{12,91}, or empirically estimated damage functions⁴⁷ and expert survey evidence⁴⁹ that points
376 towards higher overall damages. However, damages from climate change not only hit output but
377 also affect the capital stock and thus growth directly⁹²⁻⁹⁴. Finally, a considerable share of damages
378 will affect goods and services that are not traded on markets, such as environmental amenities,
379 biodiversity and coral reefs⁴⁵. These damages to non-market goods—and their associated relative
380 price changes—should be explicitly modeled and can substantially impact optimal climate policy^{16,17}.

381 **Endogenous growth:** DICE assumes an exogenous decline in technological progress, yet much of
382 modern growth theory is concerned with endogenous channels of growth⁹⁵⁻⁹⁹. Furthermore,
383 endogenous population change will likely not only impact resource demand but also affect
384 innovation^{100,101}.

385 **Abatement cost function:** The abatement function in DICE is calibrated to smooth reduction rates.
386 However, with faster rates of reduction, several non-equilibrium phenomena could make the
387 reductions more costly, e.g., through increasing levels of unemployment in certain regions. In
388 addition, if the global efforts to reduce emissions are poorly coordinated, as is the case now, with
389 certain regions paying much higher attention to the problem, then costs might also be higher than
390 what would be the case under perfect coordination^{74,102}. On the other hand, scale effects and
391 technical progress can considerably reduce abatement costs as witnessed in renewables such as
392 solar and wind in recent years. Relatedly, the marginal abatement costs curve assumed in DICE could
393 also be made endogenous, such as to feature learning-by-doing dynamics¹⁰³.

394 **Alternative ethical frameworks:** DICE builds on the standard consequentialist Discounted Utilitarian
395 welfare function that still forms the workhorse model of the economic analysis of climate policy.
396 However, the literature has proposed and applied numerous alternative ethical approaches^{22,104}.
397 Alternative welfare criteria include, among others, Sustainable Discounted Utilitarianism^{105,106}, Rank-
398 Discounted Utilitarianism¹⁰⁷, and Prioritarianism²¹.

399

400 Conclusion

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

410 Even if the UN Paris Agreement is attainable, intergenerationally fair and economically
411 optimal in our updated version of DICE, it is also necessary to consider the political
412 feasibility of meeting these stringent climate targets. One way to assess this is to investigate
413 the level of the optimal price of CO₂ and the speed of decarbonization. The mitigation
414 policies that can be pursued in practice are likely to be constrained in these dimensions, as
415 recently witnessed in response to the imposition of carbon taxes in Canada and France in
416 2018-19. While the median expert path implies a carbon price of around US\$ 100 in 2020
417 and zero emissions in 2080, the median expert's view results in an optimal CO₂ price of just
418 above US\$ 200 per ton in 2020 and complete global decarbonization by 2065. This contrasts
419 with a carbon price of around US\$80 that results from the discounting parameters of
420 Nordhaus^{1,34} in our updated model and a carbon price of around US\$ 40 in Nordhaus'
421 original DICE calibration. Thus, carbon prices resulting from the majority of expert views in
422 our updated DICE model are considerably higher than what is being implemented in most
423 sectors even in the most ambitious regions of the world. However, it is within the range of
424 what is currently used in governmental guidance for Cost Benefit Analysis, such as in
425 Germany where a SCC of around \$200¹⁰⁸ is used, or implemented as actual or effective
426 carbon taxes in certain sectors in many European countries such as the Netherlands,
427 Sweden and Switzerland¹⁰⁹. It should also be recognized that total current taxes on gasoline
428 in Europe can amount to effective taxes that far exceed our two median cases, with more
429 than \$400 per ton of CO₂ in Germany, for instance¹¹⁰. Although they are not labelled carbon
430 taxes, these policies provide some perspective on what could be possible.

431 Yet these countries are the exception and make up a small part of the global economy.
432 Furthermore, while carbon pricing is key to achieving the range of optimal climate targets
433 we present, there are major obstacles to such policy. First, there is lobbying by powerful and
434 concentrated industries. Second, there is fear of reduced competitiveness. Naturally, this is
435 mitigated if the policies are global but the fear nevertheless highlights a difficult issue of
436 policy coordination between nations. A third obstacle is the perception that carbon taxes
437 hurt the poor disproportionately¹¹¹. It is often argued that distributional concerns are a chief
438 source of resistance from significant shares of the electorate. Yet, the regressive nature of

439 carbon taxes is often exaggerated and in fact, fuel taxes are often progressive in low-income
440 countries where only the very richest have vehicles and air conditioning¹¹². Yet distributional
441 concerns may still be real in many contexts and considerable thought will have to go into
442 the design and implementation of carbon pricing in order to mitigate these widely held
443 political economy concerns^{113,114}. Perhaps one of the chief obstacles to policy stems from a
444 straightforward resistance to higher prices. In aviation, for instance, long-haul flights may
445 double in price if a carbon tax of \$300 per ton of CO₂ were levied.

446 The UN Paris Agreement is an expression of the international view that rapid action is
447 necessary to limit the damages caused by climate change. The IPCC Special Report on the
448 1.5°C target³⁶ then illustrated the measures required to meet the agreed limit of 1.5°C. In
449 this Analysis, we have shown that the benefits of limiting global warming to (well) below 2°C
450 outweigh the costs of doing so when considering updates to the most standard and
451 influential economic cost-benefit framework for climate change appraisal: Nordhaus' DICE
452 model. Our results suggest that there is no inherent disparity between the UN climate
453 targets and the principle of economic optimality. Nevertheless, enacting ambitious policies
454 remains a key challenge.

455

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473

474 Author contributions

475 M.A.D., M.C.F., B.G., M.C.H. and F.N. conceived a study on DICE focusing on the role of
476 discounting and the damage function which was merged with parallel work on the role of
477 the carbon cycle, the energy balance model and non-CO₂ forcings in DICE developed by C.A.
478 and D.J.A.J., at a workshop organized by T.S. in Gothenburg; M.C.H. performed the
479 numerical modeling, data analysis and graphical representation of results with substantive
480 input from D.J.A.J. and close feedback from M.A.D. and F.N.; the writing of the manuscript
481 was led by M.A.D., B.G., M.C.H. and F.N. with significant input from all other authors.

482

483 Authors declare no competing interests.

484 **Data Availability Statement**

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

487 **Code Availability Statement**

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

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789 Methods

790 The DICE 2016R2 model is presented in detail in Nordhaus³⁴. We implement DICE with the
791 AMPL optimization software and use the Knitro solver (version 10.2) to obtain the numerical
792 dynamic optimization results presented in this paper. Note that since we use a different
793 numerical optimization solver and modeling language than Nordhaus³⁴, our numerical
794 results differ slightly. We provide the programming code and data in separate files. To ease
795 comparability to Nordhaus^{1,34} figures, we present industrial emissions, the social cost of
796 carbon and temperature increases only until the year 2100, while the optimization runs
797 extend until 2500, as in DICE.

798 Here we provide a more detailed account of the calibration of the updated DICE model. We
799 do so by first presenting results of the baseline DICE 2016R2 of Nordhaus³⁴. In a second step
800 we summarize the updates to key climate and economics-related functional forms and
801 parameters leading to the final model specification presented in the main text. The resulting
802 climate policy paths that we present in Fig. 2 of the main text are framed in terms of what is
803 intergenerationally optimal as reflected by value judgments on the rate of pure time
804 preference and inequality aversion. Thus, we also offer a more detailed perspective on the
805 diverging views on discounting parameters, one of the key sensitivities in the economic
806 analysis of climate change. As a third step we analyze how each of the updates subsequently
807 affect climate policy paths for (i) Nordhaus' choice of discounting parameters, (ii) the
808 median expert's choice of discounting parameters, (iii) the median path, and for the 95 and
809 66 percentile ranges resulting from different expert views on intergenerational optimality.

810 Nordhaus³⁴ baseline calibration is the starting point of our analysis. The resulting pathway
811 for the social cost of CO₂, starting at 39 US\$ in 2020 and rising to 296 US\$ per ton of CO₂,
812 lies within the politically discussed range for carbon prices. Both the optimal date of
813 decarbonization in the next century and the optimal atmospheric temperature change of
814 3.5°C by 2100, rising to 4°C in the middle of the next century are far outside climate policy
815 pathways that are consistent with the UN temperature limits of 2°C and 1.5°C. We provide
816 detailed results of Nordhaus³⁴ baseline calibration in Fig. S1 of the additional Supporting
817 Information.

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

820

821 **Carbon cycle**

822 Nordhaus³⁴ writes that the 2016 version of DICE *“incorporates new research on the carbon*
823 *cycle. Earlier versions of the DICE model were calibrated to fit the short-run carbon cycle*
824 *(primarily the first 100 years). Because the new model is in part designed to calculate long-*
825 *run trends, such as the impacts on the melting of large ice sheets, it was decided to change*
826 *the calibration to fit the atmospheric retention of CO₂ for periods up to 4,000 years. Based*

827 *on studies of Archer et al.¹¹⁵, the 2016 version of the three-box model does a much better job*
828 *of simulating the long-run behavior of larger models with full ocean chemistry. This change*
829 *has a major impact on the long-run carbon concentrations.”* While this is an improvement
830 over previous DICE versions, it does not take into account non-linearities in the carbon cycle.
831 This is important since the fraction of a CO₂ emissions pulse that stays in the atmosphere at
832 any point in time in the future depends on the past cumulative emissions of CO₂. Roughly
833 the larger the cumulative emissions, the larger the fraction that remains¹¹⁵⁻¹¹⁷. Although
834 Nordhaus does not explicitly describe which model experiment in Archer et al.¹¹⁵ he uses for
835 calibrating the box model in DICE, it appears from numerical comparison of the carbon cycle
836 impulse response in DICE with those impulse responses presented in Archer et al.¹¹⁵ that the
837 calibration is based on an impulse size of 5000 GtC. That is roughly a factor five larger the
838 amount of cumulative CO₂ emissions that are compatible with the targets in the Paris
839 Agreement. Hence, given the non-linearities in the carbon cycle and climate carbon cycle
840 feedbacks, the standard carbon cycle in DICE 2016R2 underestimates the removal of CO₂
841 from the atmosphere by the biosphere and ocean when assessing emission pathways with
842 cumulative emissions considerably smaller than 5000 GtC. As a consequence of this, the
843 concentration and thus also the temperature impact of each ton of CO₂ emitted is likely to
844 be too high in DICE 2016R2 for cumulative emission levels compatible with a stabilization of
845 global mean surface temperature well below 2°C.

846 In order to deal with these issues, we change the carbon cycle in DICE 2016R2 so that it
847 takes into account the non-linearity in the carbon cycle as well as climate carbon cycle
848 feedbacks. Specifically, the linearized carbon cycle representation in DICE is changed to the
849 carbon cycle representation in the simple climate model FAIR^{29,30}, which was used to assess
850 the climate impact of various emissions pathways in the IPCC³⁶ Special Report. This enables
851 us to model a carbon cycle that is consistent with large scale carbon cycle models, such as
852 those analyzed in Archer et al.¹¹⁵, over a broad range of emission pathways, and not only
853 pathways with emission levels far above those that are consistent with the Paris Agreement.

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

857

858 **Energy balance model**

859 The temperature response to changes in radiative forcing in Nordhaus³⁴ is not consistent
860 with the response in state-of-the-art climate system models³⁷. Since the Energy Balance
861 Model (EBM) in DICE is a two-box model it has two characteristic response time scales
862 whose calibration are different than those presented in Geoffroy et al.³⁷. The rapid response
863 (yearly time scales related to the response of the well mixed upper ocean layer) is too slow
864 in DICE2016R2, while the slow response (century time scales related to the response of the
865 deep ocean) is too fast compared to advanced climate system models. The latter implies

866 that for a given radiative forcing step change the equilibrium temperature level is
867 approached too fast. We have therefore recalibrated the EBM so that its parameterization
868 represents the average characteristics of climate models used in the Coupled Model
869 Intercomparison Project Phase 5 (CMIP5)³⁷. The equilibrium response, i.e. the climate
870 sensitivity in DICE (being 3.1°C for a doubling in the CO₂ concentration), is left unchanged
871 since it fits well in the middle of the likely distribution of Equilibrium Climate
872 Sensitivity^{5,39,40}.

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

885

886 **Economic damages from climate change**

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

891 Tol⁴³ provided an influential meta-analysis of climate damages, which served as a basis for
892 previous versions of the DICE model. Both the 2009 meta-analysis and an update, Tol⁴⁴,
893 have been found to contain statistical errors²⁸. As a result Nordhaus revised the climate
894 damage function in the 2016 version of DICE^{34,46} based on his own meta-analysis of 36
895 studies that report a damage estimate. Each of these estimates is treated as an independent
896 draw from an underlying damage function. This is a precondition for using the usual
897 statistical analysis needed. However, the independence assumption can be questioned as
898 several of the estimates come from the same limited circle of authors. The selected climate
899 damage function translates a temperature increase of 3°C into a damage of 2.12% of global
900 GDP.

901 Howard and Sterner²⁸ provide an up-to-date meta-analysis of the temperature-damage
902 relationship. They find strong evidence that Nordhaus and Moffat's⁴⁶ damage estimate is
903 biased due to duplicates and omitted variables in the regression. In their preferred model²⁸
904 (Regression 4 in Table 2), total damages that include a markup of 25% for omitted non-

905 market damages from climate change are substantially higher, reaching 6.69% of global GDP
906 for a 3°C temperature increase. This is closer to recent empirical evidence⁴⁷, which shows
907 that economic damages from climate change may be even more severe, but has the merit
908 that it can be incorporated directly into the DICE model. Nordhaus¹ also used this damage
909 function in sensitivity analysis. Extended Data Fig. 3 compares the baseline to the isolated
910 effect of the updated optimal economic damage from climate change (as a percentage of
911 global GDP) under Nordhaus' discounting choices. Damages are substantially higher in the
912 updated model for most of the time horizons considered.

913

914 **Intergenerational welfare**

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

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

931 The “median expert path” represents the median of all model runs for the SCC, temperature
932 and emissions associated with each of the 173 experts' chosen pair of discounting
933 parameters at each point in time. The “median expert path” has a theoretical justification in
934 the literature on voting outcomes. It can be interpreted as the voting outcome if experts
935 have single-peaked preferences, and vote over a specific end point of a climate path at a
936 given point in time⁵⁸, instead of parameters as in the case for the “median expert view”.
937 Hence, a given “median expert path” tracks voting outcomes for a given climate path at any
938 given point in time.

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

943 It should be noted that a major finding of the expert survey is that a majority of experts do
944 not follow the simple Discounted Utilitarian approach and associated Ramsey rule (See Box
945 1), but deviate for a number of reasons²⁴. These include project risk, uncertainty,
946 environmental scarcity, effects of inequalities within generations as well as alternative
947 ethical approaches (See Box 2). As the mean (median) imputed simple Ramsey rule in the
948 expert survey is higher than the recommended mean (median) social discount rate, these
949 extensions are likely to lead to recommending more stringent climate policy. The main text
950 may therefore depict conservative results.

951

952 **Non-CO₂ forcing**

953 Abatement of non-CO₂ emissions are critical when aiming for stringent climate stabilization
954 levels^{2,36}. The scenario assumption for the radiative forcing from non-CO₂ climate forcers in
955 Nordhaus³⁴ is exogenously given. It is substantially higher compared to what is estimated in
956 other climate scenario work analyzing pathways compatible with stabilization of global
957 mean surface temperature around 1.5-3°C above the pre-industrial level, e.g., the
958 Representative Concentration Pathways (RCP) 2.6 and 4.5¹¹⁹ or the Shared Socioeconomic
959 Pathways (SSP) towards 1.9 W/m²¹¹⁸. While several of these abatement options for non-
960 CO₂ emissions might not be cost-effective at modest carbon prices as those suggested in the
961 original DICE model (39 US\$ in 2020), it very likely becomes cost effective to abate non-CO₂
962 greenhouse gases if governments implement policies that will meet current UN climate
963 targets^{2,120}. This implies that the exogenously set radiative forcing pathway for non-CO₂
964 emissions in DICE is too high for the majority of our optimal policy runs. We therefore
965 consider a pathway of non-CO₂ greenhouse gases that is better aligned to the CO₂ price and
966 temperature levels we obtain with the updated version of DICE. Specifically, we have
967 changed the radiative forcing scenario from non-CO₂ forcers so that it matches the path of
968 the REMIND integrated assessment model using the SSP2 scenario meeting a non-CO₂
969 forcing level of 2.6 W/m² in 2100³¹. This scenario reaches similar carbon concentrations,
970 radiative forcing and temperature levels as obtained in our fully updated DICE model. In the
971 Extended Data Fig. 4, we compare the standard to the updated path for non-CO₂ forcing in
972 isolation.

973

974 **Negative emissions technologies**

975 A key difference between the DICE and the IPCC Special Report³⁶ is the stance regarding the
976 availability of carbon removal technologies leading to net negative emissions. While the
977 scenarios considered by the IPCC^{2,36} make use of negative emission technologies roughly by
978 the year 2050, the DICE 2016R2 model assumes that this will only be feasible from 2160
979 onwards. In line with the pathways assessed in the IPCC report, we allow for the possibility
980 of negative emissions technologies from mid-century onwards. We set the upper level of
981 abatement to 120% of baseline emissions as in DICE 2016R2. Consequently, emissions reach

982 -18 GtCO₂ per year for the lower 95% bound of expert views on discounting by 2100. For
983 comparison, the emission pathways that are assessed in IPCC SR 1.5 and that meet the 1.5°C
984 level by 2100 have a median emission level of -12 GtCO₂ per year in 2100, with a 90%
985 interval of -20 GtCO₂ per year to -2.3 GtCO₂ per year, while the emissions level in 2070 has a
986 median of -8.0 GtCO₂ per year and a 90% interval of -15 GtCO₂ per year to -0.70 GtCO₂ per
987 year (estimated from data available in IAMC 1.5°C scenario explorer⁷²). The timing of the
988 availability of negative emissions technologies as well as their potential magnitude are still
989 intensely debated^{69,70}, and will ultimately, similar to all abatement technologies, depend on
990 the interplay of technological development and (expected) carbon prices.

991

992 **Feasibility constraints**

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

1000

1001 **Optimal climate policy paths under updated model specifications**

1002 **First**, we now consider the introduction of the new carbon cycle dynamics. Extended Data
1003 Fig. 5 shows how different positions on social discounting translate into plausible ranges of
1004 climate policy paths in DICE 2016R with the new updated carbon cycle.

1005 The maximum SCC in the 66 (95) percentile range are \$277 (\$1017) in the year 2020 and
1006 \$1080 (\$2310) in 2100. By contrast, the minimum SCC in 2020 in the 66 (95) percentile
1007 range is \$16 (\$3) increasing to \$161 (\$24) in 2100. Nordhaus' SCC is at \$25 in 2020 and \$245
1008 in 2100. By contrast, the median expert view translates into a SCC of \$140 in 2020,
1009 increasing to \$742 in 2100. The median path in turn results in a SCC of \$43 in 2020,
1010 increasing to \$484 in 2100.

1011 In the central 66 percentile plausible range, the decarbonization of the global economy
1012 occurs 5 years later compared to the baseline model; the economy should either be
1013 decarbonized in 2045 or 2135. In Nordhaus' best-guess, the economy would not be
1014 decarbonized within this century, while optimal decarbonization takes place by 2065 in the
1015 median expert's view. The median path in turn results in decarbonization by 2090.

1016 While Nordhaus' view on social discounting translates into 3.27°C warming by 2100, the
1017 median expert view (median paths) leads to an increase in temperature of 2.43°C (2.93°C)
1018 by 2100. In the 66-percentile range, the temperature increase in 2100 is as high as 3.43°C
1019 (3.53°C) at the upper end, and 2.13°C (2.0°C) at the lower end. Moreover, none of the

1020 model runs that result from the expert views would lead to an optimal policy that stays
1021 within the 1.5°C limit of the Paris Agreement. Overall, only 6% of all model runs stay below
1022 2°C by 2100.

1023 **Second**, we add the updated energy balance model. Extended Data Fig. 6 shows how
1024 different positions on social discounting translate into plausible ranges of climate policy
1025 paths in DICE 2016R2 with updated carbon cycle and energy balance model.

1026 Compared to the model that only incorporates the updated carbon cycle the SCC decrease
1027 in almost all model runs. The maximum SCC in the 66 (95) percentile range are \$221 (\$752)
1028 in the year 2020 and \$887 (\$1720) in 2100. By contrast, the minimum SCC in 2020 in the 95
1029 (66) percentile range is \$6 (\$18) increasing to \$41 (\$161) in 2100. The SCC using the
1030 discounting parameters of Nordhaus remains at \$25 in 2020 and increases to \$245 in 2100.
1031 By contrast, the median expert view results in a SCC of \$113 in 2020, increasing to \$609 in
1032 2100. The median path in turn leads to a SCC of \$38 in 2020, increasing to \$406 in 2100.

1033 In the central 66 percentile plausible range, the economy should either be decarbonized in
1034 2055 or 2190. In Nordhaus' best-guess, the economy would not be decarbonized within this
1035 century, while optimal decarbonization takes place by 2065 in the median expert's view.
1036 The median path in turn results in decarbonization by 2090. Hence, the introduction of the
1037 updated energy balance model shifts optimal decarbonization into the future.

1038 While Nordhaus' view on social discounting now translates into 2.97°C warming by 2100,
1039 the median expert view (median paths) leads to an increase in temperature of 2.14°C
1040 (2.61°C) by 2100. In the 95% (66%) range, the temperature increase in 2100 is 3.27°C
1041 (3.12°C) at the upper end, and 1.63°C (1.83°C) at the lower end. Moreover, still none of the
1042 model runs that result from the expert views would lead to an optimal policy that stays
1043 within the 1.5°C limit of the Paris Agreement. Overall, now 23% of all model runs stay below
1044 2°C by 2100.

1045 **Third**, we add the updated temperature-damage relationship according to Howard and
1046 Sterner²⁸. Extended Data Fig. 7 shows how different positions on social discounting translate
1047 into plausible ranges of climate policy paths in DICE 2016R2 with updated carbon cycle,
1048 energy balance model and temperature-damage relationship.

1049 Compared to the model that incorporates the updated carbon cycle and energy balance
1050 model only, the SCC is, not surprisingly, increased quite markedly by the introduction of the
1051 new damage function. The maximum SCC in the 66 (95) percentile range are \$568 (\$2363)
1052 in the year 2020 and \$2203 (\$5345) in 2100. By contrast, the minimum SCC in 2020 in the 95
1053 (66) percentile range is \$19 (\$56) increasing to \$129 (\$448) in 2100. Nordhaus' SCC is \$76 in
1054 2020 and increasing to \$593 in 2100. By contrast, the median expert view leads to a SCC of
1055 \$289 in 2020, increasing to \$1464 in 2100. The median path in turn results in a SCC of \$113
1056 in 2020, increasing to \$995 in 2100.

1057 In the central 66 percentile plausible range, the economy should either be decarbonized in
1058 2025 or 2090. In Nordhaus' best-guess, the economy would be decarbonized by 2080, while

1059 optimal decarbonization takes place by 2040 in the median expert's view. The median path
1060 in turn results in decarbonization by 2065. Hence, the introduction of the updated
1061 temperature-damage relationship means that optimal decarbonization occurs sooner.

1062 While Nordhaus' view on social discounting now translates into 2.24°C warming by 2100,
1063 the median expert view (median paths) leads to an increase in temperature of 1.71°C
1064 (2.02°C) by 2100. In the 95 (66) percentile range, the temperature increase in 2100 is 2.97°C
1065 (2.46°C) at the upper end, and 1.63°C (1.63°C) at the lower end. Moreover, still none of the
1066 model runs that result from the expert views would lead to an optimal policy that stays
1067 within the 1.5°C limit of the Paris Agreement. However, with updated damage function, 57%
1068 of all model runs stay below 2°C by 2100.

1069
1070 Howard and Sterner²⁸ provide an update on how damage estimates are combined to
1071 calibrate the standard damage function, but abstract from "catastrophic" climate damages.
1072 In the following, we run the DICE model with updated carbon cycle and energy balance
1073 model with the Weitzman⁵⁰ damage function calibrated to incorporate damages of 2.9%
1074 (50%) in units of output for a temperature increase of 3°C (6°C). Fig. S3 in the additional
1075 Supporting Information shows how different positions on social discounting translate into
1076 plausible ranges of climate policy paths in DICE 2016R2 with updated carbon cycle, energy
1077 balance model and temperature-damage relationship as in Weitzman⁵⁰. Overall, the results
1078 show much less stringent climate policy as compared to the case with the Howard and
1079 Sterner²⁸ damage function. This is because, for up to 3°C temperature increase, the
1080 Weitzman⁵⁰ damage function has a similar shape as compared to the Nordhaus³⁴ damage
1081 function. Only for higher temperature increases, the "catastrophic" damages kick in, leading
1082 to 50% output loss for 6°C warming. Thus, in the relevant range of climate policy measures
1083 that are optimal according to DICE with updates carbon cycle and energy balance model (for
1084 example 3.27°C temperature increase by 2100 at the upper 95% bound), the "catastrophic"
1085 part of Weitzman's⁵⁰ damage function does not become relevant.

1086 **Fourth**, we add the updated exogenous path for non-CO₂ forcing. Extended Data Fig. 8
1087 shows how different positions on social discounting translate into plausible ranges of
1088 climate policy paths in DICE 2016R2 with updated carbon cycle, energy balance model,
1089 temperature-damage relationship and non-CO₂ forcing.

1090 The updated non-CO₂ forcing scenario reflects an improved management of non-CO₂
1091 emissions in line with the SCC and temperature levels we got after having updated the
1092 damage function. The maximum SCC values thus decrease; in the 66 (95) percentile range
1093 they are \$358 (\$1059) in the year 2020 and \$1258 (\$2193) in 2100. By contrast, the
1094 minimum SCC in 2020 in the 95 (66) percentile range is \$19 (\$54) increasing to \$121 (\$377)
1095 in 2100. Nordhaus' SCC is \$72 in 2020 and increasing to \$491 in 2100. By contrast, the
1096 median expert view leads to a SCC of \$229 in 2020, increasing to \$1006 in 2100. The median
1097 path in turn results in a SCC of \$106 in 2020, increasing to \$761 in 2100.

1098 In the central 66 percentile plausible range, the economy should either be decarbonized in
1099 2035 or 2100. In Nordhaus' best-guess, the economy would be decarbonized in 2085, while
1100 optimal decarbonization takes place by 2050 in the median expert's view. The median path
1101 in turn results in decarbonization by 2070.

1102 While Nordhaus' view on social discounting now for the first time translates into staying
1103 below the 2°C temperature target (1.98°C warming by 2100), the median expert view
1104 (median paths) leads to an increase in temperature of 1.44°C (1.75°C) by 2100. In the 95
1105 (66) percentile range, the temperature increase in 2100 is 2.68°C (2.21°C) at the upper end,
1106 and 1.28°C (1.32°C) at the lower end. For the first time the 1.5°C temperature target by
1107 2100 is in line with optimal economic policy according to a third of the 173 expert views on
1108 social discounting. Three quarters of all model runs stay below 2°C by 2100.

1109 **Fifth**, we make negative emissions technologies available in 2050 instead of 2160 in
1110 DICE2016R2. Extended Data Fig. 9 shows how different positions on social discounting
1111 translate into plausible ranges of climate policy paths in DICE 2016R2 with updated carbon
1112 cycle, energy balance model, temperature-damage relationship, non-CO₂ forcing and
1113 negative emissions technologies available by 2050.

1114 The earlier availability of negative emissions technologies increases the emissions budget in
1115 line with any given temperature target. The maximum SCC values in the 66 (95) percentile
1116 range are \$242 (\$425) in the year 2020 and \$630 (\$640) in 2100. By contrast, the minimum
1117 SCC in 2020 in the 95 (66) percentile range is \$19 (\$54) increasing to \$113 (\$362) in 2100.
1118 Nordhaus' SCC is \$70 in 2020 and increasing to \$446 in 2100. The median expert view leads
1119 to a SCC of \$199 in 2020, increasing to \$575 in 2100. The median path in turn results in a
1120 SCC of \$103 in 2020, increasing to \$569 in 2100.

1121 In the central 66 percentile plausible range, the economy should either be decarbonized in
1122 2060 or 2100. In Nordhaus' best-guess, the economy would be decarbonized in 2090, while
1123 optimal decarbonization takes place by 2070 in the median expert's view. The median path
1124 in turn results in decarbonization by 2080.

1125 While Nordhaus' view on social discounting translates into 2.01°C warming by 2100, the
1126 median expert view (median paths) leads to an increase in temperature of 1.38°C (1.75°C)
1127 by 2100. In the 95 (66) percentile range, the temperature increase in 2100 is 2.63°C (2.23°C)
1128 at the upper end, and 0.90°C (1.20°C) at the lower end. 38% of all model runs stay within
1129 the 1.5°C limit of the Paris Agreement and 76% of all model runs stay below 2°C by 2100.

1130 As the last step, we add the described technology inertia constraints resulting in Figure 2 in
1131 the main text.

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Intergenerational Welfare

4

CLIMATE

EXOGENOUS CO₂ EMISSIONS (LAND USE)

TOTAL CO₂ EMISSIONS

INDUSTRIAL CO₂ EMISSIONS

CARBON CYCLE

ATMOSPHERE

BIOSPHERE AND OCEANS

1

Negative Emission Technologies

6

DECARBONIZATION

Feasibility

7

CLIMATE SYSTEM

5 EXOGENOUS NON-CO₂ FORCING

TOTAL RADIATIVE FORCING

2

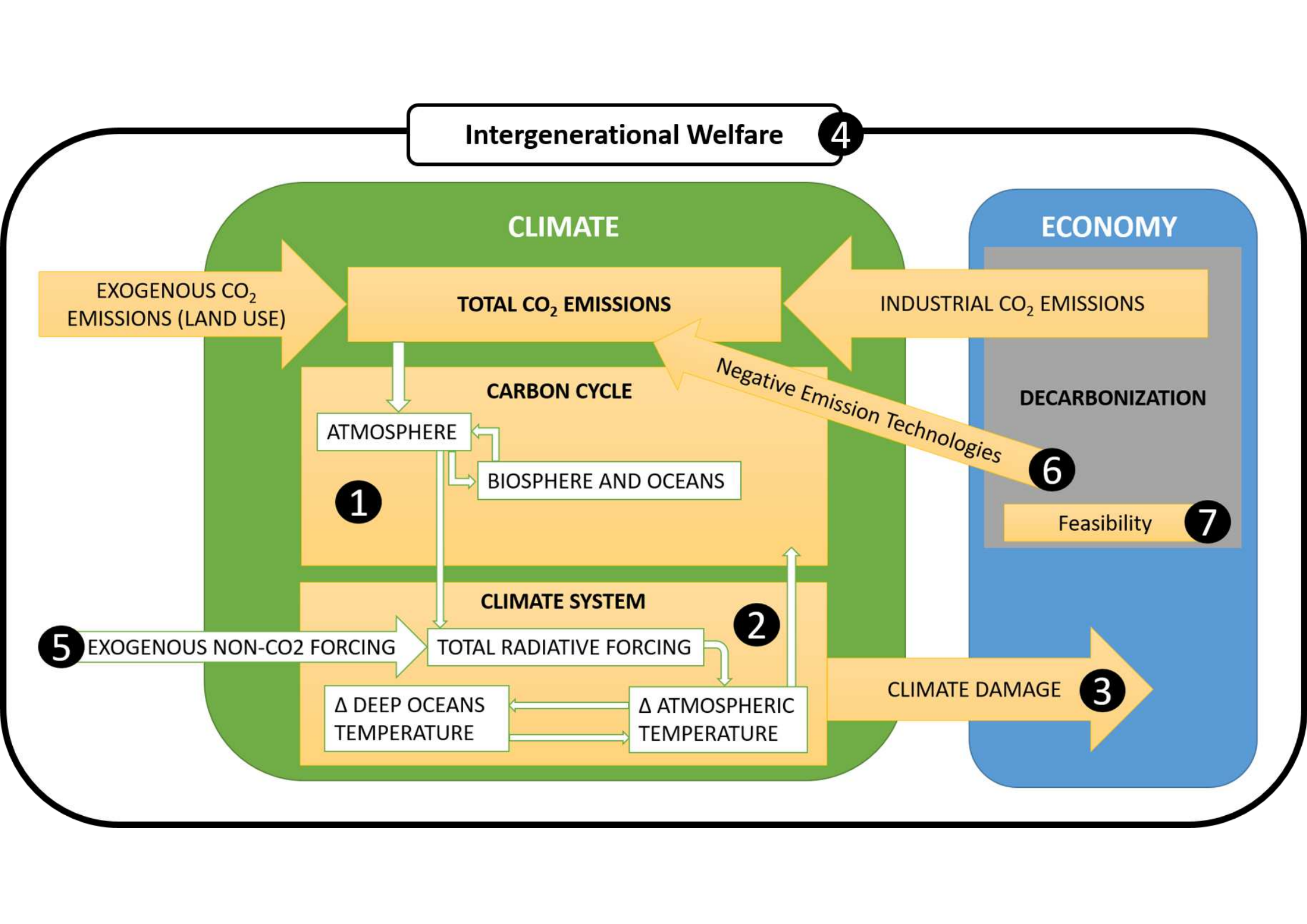
Δ DEEP OCEANS TEMPERATURE

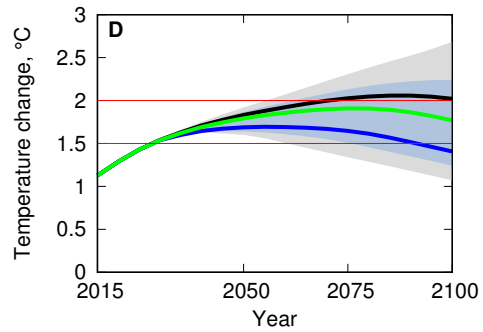
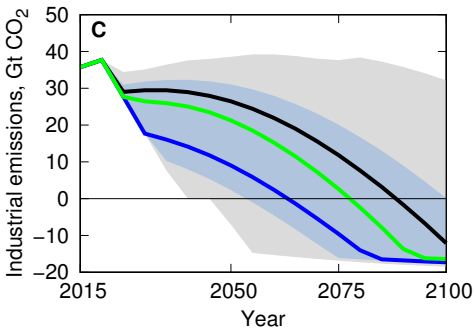
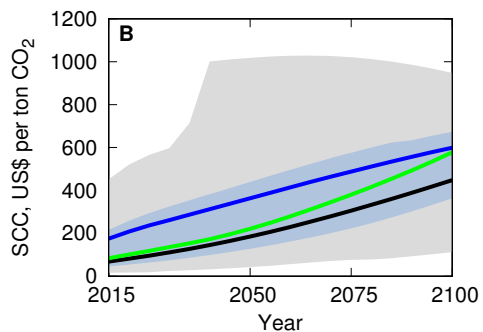
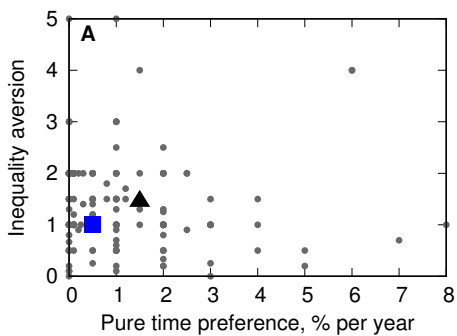
Δ ATMOSPHERIC TEMPERATURE

CLIMATE DAMAGE

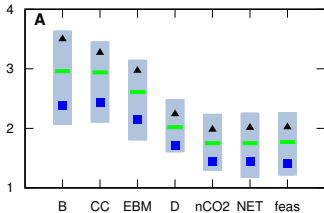
3

ECONOMY

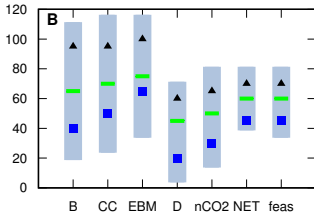




Temperature change 2100, °C



Years to decarbonization from 2020



SCC 2020, US\$ per ton CO₂

