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Cost-effective implementation of the Paris Agreement using flexible greenhouse gas metrics

(Short title: Flexible emission metrics for the Paris Agreement)

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22 **Abstract**

23 Greenhouse gas (GHG) metrics, that is, conversion factors to evaluate the emissions of non-CO₂ GHGs on
24 a common scale with CO₂, serve crucial functions in the implementation of the Paris Agreement. While
25 different metrics have been proposed, their economic cost-effectiveness has not been investigated under a
26 range of pathways, including those significantly overshooting the temperature targets. Here we show that
27 cost-effective metrics for methane that minimize the overall mitigation costs are time-dependent, primarily
28 determined by the pathway, and strongly influenced by temperature overshoot. Parties to the Paris Agreement
29 have already adopted the conventional 100-year Global Warming Potential (GWP100), which is shown to
30 be a good approximation of cost-effective metrics for the coming decades. In the longer term, however, we
31 suggest that parties consider adapting the choice of common metrics to the future pathway as it unfolds, as
32 part of the recurring global stocktake, if global cost-effectiveness is a key consideration.

33

34 **INTRODUCTION**

35 Aligning climate policies with the goals of the Paris Agreement implies to revisit the concept of GHG metrics.
36 Emission metrics offer a simple way to quantify the combined climate impacts from the emissions of a mix
37 of radiatively active gases and aerosols, without requiring a model. Specifically, a metric serves as an
38 exchange index to convert the emission of a non-CO₂ climate forcer to a so-called “CO₂-equivalent emission”
39 for climate policy purposes (Fig. 1). Emission metrics have, however, been a subject of debate and evaluation
40 (1, 2), since the inception of GWP (3, 4) in 1990. GWP100, the most widely used metric today, equates the
41 emissions of different climate forcers with respect to the radiative forcing integrated over 100 years after a
42 pulse emission (2). The consistency of GWP100 with policy goals has been questioned from physical and
43 economic perspectives, and many alternatives have been proposed (5-15). The choice of metrics also reflects
44 the priority for issues of concern (16, 17), influencing particularly how much the emissions of CH₄, a short-
45 lived climate forcer (SLCF) and currently the second most important source of radiative forcing after CO₂
46 (2), should be reduced relative to those of CO₂, which is of considerable importance in high CH₄-emitting
47 countries (Fig. S1). While the scientific debate on metrics continues (18, 19), GWP100 has been adopted as
48 the common metrics for the Paris Agreement implementation (20). Adopting common metrics for all parties
49 to the Paris Agreement was a vital advance in the development of the so-called Paris Rulebook since it will
50 enable cross-party comparisons of progress toward respective nationally determined contributions (NDCs),

51 allow assessing the effect of specific mitigation actions and policies put in place, and permit trading of credits
52 between parties. However, it is unclear how costly this decision will be if GWP100 is the metric that will be
53 permanently used for future mitigation strategies.

54 Here we evaluate the use of GWP100 and other emission metrics in climate mitigation strategies
55 on the basis of their cost-effectiveness in reference to the Paris Agreement temperature targets. The cost-
56 effectiveness is one of the key principles of the United Nations Framework Convention on Climate Change
57 (UNFCCC) (Article 3 of ref. (21)), as well as a guiding principle for climate mitigation pathways presented
58 in the previous Intergovernmental Panel on Climate Change (IPCC) Assessment Reports. We use a simple
59 globally aggregated Integrated Assessment model (IAM) (22, 23) that accounts for distinct atmospheric
60 characteristics and emission abatement costs of CO₂ and CH₄ among other features. This model is used to
61 derive a cost-effective pathway for a given temperature target and explore how the use of a metric can
62 influence the pathway and mitigation costs. The analysis was performed for a contrasted range of pathways
63 toward the Paris Agreement temperature target levels, including those significantly overshooting the 2 °C
64 target level temporarily, which were not assessed in the IPCC Special Report “Global warming of 1.5 °C”
65 (SR15) (24). Low overshoots (i.e. exceedance warming of up to 0.1 or 0.2 °C) have been considered in
66 previous related studies (25-28); however, higher overshoots above 2 °C – reflecting the current policy trend
67 (i.e. ~3 °C warming by 2100 (29, 30)) – have not been considered before despite their increasing likelihood.
68 Overshoot pathways are intended to illustrate the relatively unexplored scenarios in which the world would
69 fail to take stronger near-term climate actions that would have been consistent with the Paris Agreement,
70 which is however followed by very deep mitigation allowing a recovery from overshoot.

71 Examining the costs of using metrics in light of overshoot possibilities illuminates their path-
72 dependency. According to our IAM, the cost-effective metric for CH₄ (i.e. the ratio of the shadow prices of
73 CO₂ and CH₄), which is known to be time-dependent under stabilization pathways (7), shows larger temporal
74 variations under overshoot pathways. The path- and time-dependency of cost-effective metrics led us to
75 explore further how the choice of conventional CH₄ metrics such as GWP100, GWP50, and GWP20 can be
76 adapted in policy setting to evolving future pathways. We show that the *adaptive* use of metrics – changing
77 from GWP100 to other shorter time horizon GWPs in the future – can save mitigation costs, compared to
78 the *permanent* use of GWP100. Nevertheless, GWP100 appears to be a reasonably good approximation of
79 cost-effective metrics for the next few decades. Hence, our study suggests that the UNFCCC and parties to

80 the Paris Agreement should consider periodically assessing the appropriateness of the choice of GHG metrics
81 as future options unfold to pursue a cost-effective implementation of emissions abatement options. Such
82 assessments could be considered as part of the recurring global stocktake processes within the UNFCCC
83 over the coming decades, where future mitigation actions and ambition levels are discussed among parties,
84 since they are related to potential revisions of the adopted GHG metrics.

85

86 Aligning emission metrics with emerging mitigation strategies

87 The framing of climate policy-relevant research has changed drastically with the adoption of the Paris
88 Agreement in 2015 (31), which calls for holding the global warming well below 2 °C, pursuing efforts to
89 limit the warming to 1.5 °C relative to preindustrial levels (Article 2.1), and achieving global net zero
90 anthropogenic GHG emissions during the latter half of this century (Article 4.1). The temperature targets
91 have led to massive research efforts on low temperature stabilization pathways, as assessed in the IPCC
92 SR15. The SR15 highlighted the need for global net zero anthropogenic CO₂ emissions by 2050 to achieve
93 the 1.5 °C goal. An increasing number of countries, municipalities, sectors, and individual firms adopted so-
94 called “carbon neutrality”, or zero emissions, for mid-century.

95 In contrast to these ambitious goals, the current policies imply that the global warming may reach
96 3 °C by the end of this century (29, 30). While there are pressures to ratchet up the NDCs (32), even planned
97 mitigation efforts may face challenges upon implementation. The demonstrations by the Yellow Vests
98 (“gilets jaunes” in French), triggered in November 2018 by the opposition to rising fuel tax in France, were
99 illustrative of the difficulties of implementing climate policies. In 2020, the global CO₂ emissions were
100 significantly dropped relative to the 2019 level as a result of the pandemic of coronavirus disease 2019
101 (COVID-19) (33). To enable emission reductions for a longer term, a set of green policies have been
102 proposed as part of the recovery packages (34), but it is yet unclear how the long-term emission trend will
103 unfold. Given these circumstances, as argued by others before (35-37), it is imperative to consider a broad
104 range of pathways, not only stabilization (i.e. non-overshoot) and low overshoot pathways toward the 2 and
105 1.5 °C targets but also higher overshoot pathways, under which the temperature exceeds the target levels
106 significantly before eventually settling there. Pathways overshooting the 1.5 °C target and staying below
107 2 °C can be interpreted as being in line with the Paris Agreement’s long-term goal, while pathways
108 significantly overshooting the 2 °C target should be seen as being in violation of the goal. Nevertheless, such

109 overshoot pathways must be considered plausible if ambition levels are not rapidly increased in the next
110 decades. However, higher overshoot pathways, in particular those substantially exceeding the 2 °C level, are
111 underrepresented in the recent literature or rarely found in IAM studies conducted after the adoption of the
112 Paris Agreement. GHG metrics were evaluated for various temperature and forcing targets (18, 25, 27, 38),
113 with a few studies analyzing metrics directly applied to the net zero GHG target (23, 39). But, to our
114 knowledge, metrics have not been investigated under a range of plausible overshoot pathways in relation to
115 the Paris Agreement goals.

116 At the twenty-fourth session of the Conference of the Parties (COP24) of the UNFCCC, GWP100
117 was adopted as the common metrics to be used for the implementation of the transparency framework of the
118 Paris Agreement (paragraph 37 of the Annex to Decision 18/CMA.1 (20)). The transparency framework
119 includes guidelines for parties’ GHG inventories, scenario analyses, and reporting on implemented policies
120 and measures, with the purpose of tracking progress with the implementation of each party’s NDC and
121 informing the global stocktake (paragraph 1 of the Annex to Decision 18/CMA.1 (20)). To be more specific,
122 the guideline states that the GWP100 values shall be used as provided by the IPCC Fifth Assessment Report
123 (AR5) (or a subsequent IPCC report upon future agreement), an update from those provided by the IPCC
124 Second or Fourth Assessment Report (SAR or AR4) currently in use at the UNFCCC (40). The COP24
125 decision gave an option for using other metrics in addition to GWP100, noting the Global Temperature
126 change Potential (GTP) (8) as an example, which equates the emissions of different climate forcings with
127 respect to the final *temperature change* at the *end* of a chosen time horizon after a pulse emission.

128 While the decision has been made on the common metrics for the implementation of the Paris
129 Agreement, it is important to emphasize that the COP24 decision contains a provision for reviewing and
130 updating the guidelines for the transparency framework by 2028 at the latest (paragraph 3 of Decision
131 18/CMA.1 (20)) that could allow a shift from GWP100 towards another type of common metrics, provided
132 that parties wish to pursue such an update that goes beyond the current decision. It should be further noted
133 that the topic of common metrics is still listed as one of the sub-items of Methodological issues in the draft
134 provisional agenda for the fifty-second session of the Subsidiary Body of Scientific and Technological
135 Advice (SBSTA52) (41), an advisory body to the UNFCCC on scientific and technical matters. The
136 negotiations at SBSTA did not reach conclusions at the previous session and the agenda item is automatically
137 pushed to the next session planned for 2021. Nevertheless, the draft text (42) proposed by the Chair of the

138 previous session suggests that parties recognize the importance of synchronizing metrics used for different
139 purposes within the UNFCCC, guided by the decision made for the transparency framework of the Paris
140 Agreement. At the same time, the draft text shows openness to considering future scientific findings on
141 metrics in IPCC AR6, as well as views of parties and observers on the implications of the choice of metrics
142 for climate change policy. In response, a group of scientists made a voluntary submission to UNFCCC to
143 encourage SBSTA52 to initiate and conclude a review of common metrics, via a dialogue between
144 policymakers and the research community (43).

145

146 **RESULTS**

147 Cost-effective metrics under stabilization and overshoot pathways

148 We present a first analysis of the implications of using different emission metrics under stabilization and
149 overshoot pathways. To start with, we show the Global Cost-effective Potential (GCP) (7, 44), the
150 economically effective metric that can be derived from a cost-effective pathway of interest, which serves as
151 a benchmark in the analysis that follows. Unlike GWP and GTP, which require only a physical model to be
152 estimated, GCP requires calculations of both climate change and mitigation costs with an IAM. Our study
153 employs the Aggregated Carbon Cycle, Atmospheric Chemistry, and Climate model (ACC2) version 4.3 (22,
154 23) (Methods), a simple IAM that describes major physical and biogeochemical processes in the global earth
155 system, as well as the economic relationships between mitigation levels of GHG emissions and associated
156 costs. More specifically, ACC2 consists of a global climate and carbon cycle model of reduced complexity
157 combined with an economic module containing marginal abatement cost (MAC) curves for CO₂, CH₄, and
158 N₂O (38, 45) (Fig. S2). This model allows us to generate cost-effective emission pathways for given
159 temperature targets under a single modeling framework, unlike other more complex IAMs that are not
160 dynamically coupled with a climate and carbon cycle model. The model describes primarily global aspects,
161 providing no details in regional and sectoral changes. The temporal resolution of the model is one year.
162 Limitations associated with the MAC curve approach are discussed in Methods and elsewhere (46, 47). It
163 needs to be kept in mind that our pathways are illustrative only and should be interpreted as such.

164 We generated 2 °C stabilization as well as 2 °C and 1.5 °C overshoot pathways on the basis of a
165 cost-effectiveness principle by minimizing the net present value costs of abating the GHG emissions over
166 time as calculated from the MAC curves (Fig. 2a; Table S1; Fig. S3). Fig. 2a shows five such illustrative

167 pathways in comparison to those considered in SR15 (48) (Methods). We assume two different overshoot
168 levels requiring the warming not to exceed the respective target after 2100 or 2150. For example, we applied
169 a 2 °C target beginning in 2100 in the cost-effective pathway calculation to derive our 2 °C pathway with
170 overshoot until 2100. Thus, the length and magnitude of temperature overshoot were not externally set in
171 our analysis but rather an outcome of our internal cost-effective pathway calculations, reflecting various
172 model assumptions (Fig. S6) including, most notably, the limits to negative CO₂ emissions. The time scale
173 beyond 2100 is essential for investigating a broad range of overshoot pathways aligning the current trend
174 toward a 3 °C warming before the end of this century. We interpret the two temperature targets stated in
175 Article 2 as stabilization targets (i.e. stable temperatures) in our analysis. Out of the five illustrative pathways,
176 only two pathways, namely the 2 °C stabilization pathway and the 1.5 °C medium overshoot pathway, are
177 generally considered as being consistent with the Paris Agreement. The remaining three pathways are
178 intended to cover the relatively unexplored but increasingly relevant range reflecting current policy levels.
179 These three cases illustrate how the pathway would appear if climate actions were insufficient in the near-
180 term but were enhanced later to still aim for the target levels. The three pathways show a recovery from
181 overshoot derived under our model assumptions (Methods); however, the recovery in reality is contingent
182 on the feasibility of very deep mitigation. The GHG emissions (based on GWP100) in these three pathways
183 go below zero by around the turn of this century (Fig. S3j), which may be interpreted as being consistent with
184 the Paris Target emission target (23); however, these cases should be regarded as a violation of the Paris
185 Agreement because of the significant overshoot above 2 °C. Note that no 1.5 °C stabilization pathway is
186 included in our analysis because the 1.5 °C target cannot be achieved without overshoot in our model unless
187 we relax the abatement constraints (Methods) (23). The earliest possible year to achieve the 1.5 °C target is
188 2085 after an overshoot of 0.35 °C (in 2049) under our default model assumptions. Sensitivities of these
189 pathways to underlying assumptions are discussed where appropriate below.

190 Under each of these five pathways, we calculated GCP, a metric most consistent with the cost-
191 effectiveness principle. GCP is defined as the ratio of the willingness to pay for emitting an additional unit
192 of a gas of interest to that of CO₂ at each point in time under a cost-effective pathway, reflecting the ratio of
193 the emission shadow prices between the two gases. We implicitly assume a globally connected emission
194 market (or a global emission tax system) for CO₂, CH₄, and N₂O. In this analysis, we focus on the outcome
195 of CH₄, a potent GHG whose atmospheric response time is substantially shorter than that of CO₂ (49). The

196 outcome of N₂O, a long-lived GHG, is different but does not strongly influence the overall outcome, so it
197 will not be analyzed here.

198 Our calculations show that, under the 2 °C stabilization pathway, the CH₄ GCP rises over time
199 until the temperature reaches 2 °C (Fig. 2b) (7, 12, 38). GCP for CH₄ is larger than GTP100 throughout the
200 period and becomes larger than GWP100 (i.e. 28 in the IPCC AR5) after 2040. After the stabilization in
201 2063, GCP stays at an approximately constant level near GWP50. For the overshoot pathways, the rise in
202 the CH₄ GCPs occurs later and more drastically than under the stabilization pathway. GCPs grow after the
203 temperature peak, until immediately before the temperature returns to the target levels, with a peak exceeding
204 GWP20. The rise in the CH₄ GCPs is associated with the priority given to CH₄ mitigation to lower the
205 temperature to the target level (Fig. S4). This is because of the rapid effect CH₄ mitigation has on the
206 temperature, but other factors also come into play. Such deep CH₄ abatement prior to the stabilization was
207 not observed under the stabilization pathway. Once the target is met, the temperature does not have to be
208 reduced further in our cost-effectiveness approach, which reduces the relative incentive to abate CH₄
209 emission, resulting in the abrupt drop in GCPs. The temperature is slightly decreased further after the
210 stabilization due to the inertia of the physical earth system before it finally settles at the target level.

211 Our results from the five illustrative pathways of Fig. 2 show that the CH₄ GCP is time-dependent,
212 rises till stabilization occurs – particularly strongly so under the overshoot pathways – and then becomes
213 stable after stabilization. The long-term evolution of GCP depends on the type of pathways. Overshoot
214 pathways imply larger changes in GCP. These results also suggest that the evolution of GCP is largely
215 determined by the year when the stabilization is eventually achieved (related insight in ref. (12)) and
216 relatively insensitive to the target level (Fig. S5), but not at all influenced by the year of the temperature
217 peak. We further explore the sensitivity of GCP with respect to the assumptions on the equilibrium climate
218 sensitivity (2 °C and 4.5 °C, with 3 °C by default), the discount rate (2% and 6%, with 4% by default), and
219 the MAC curves (one case assuming a 50% higher CO₂ MAC curve and 50% lower CH₄ and N₂O MAC
220 curves than the respective standard MAC curves and the opposite case assuming a 50% lower CO₂ MAC
221 curve and 50% higher CH₄ and N₂O MAC curves than the respective standard MAC curves) (Methods).
222 GCP is sensitive to the assumptions on the discount rate and the equilibrium climate sensitivity, while being
223 less sensitive to the MAC curves (12); however, the general behavior of GCP described above holds under
224 different assumptions in our IAM (Fig. S6).

225

226 The cost-effectiveness of GWPs and GTPs

227 The time-dependent GCP is the cost-effective metric by construction, as it is derived directly from the cost-
228 effective pathway calculation. We now estimate the economic implications of continuing with the time-
229 invariant GWP100 currently in use and agreed to be used in the Paris Agreement implementation. The
230 economic costs of using GWP100 can be calculated by imposing the metric in the pathway calculation,
231 namely, on the ratios of the marginal abatement costs of associated gases at each point in time. That is, one
232 keeps the CH₄ marginal abatement cost in each year to be larger than the CO₂ marginal abatement cost in
233 the same year by a factor of the CH₄ GWP100. Likewise, one applies the N₂O GWP100 to fix the ratio of
234 the CO₂ and N₂O marginal abatement costs over time (but this constraint on N₂O has only small impact on
235 the overall results). Thus, the use of metrics poses additional constraints in the pathway calculation, giving
236 rise to higher mitigation costs than those without the use of metrics. The cost increment (in terms of the
237 discounted net present value) as a result of the metric use, relative to the lowest costs without the use of
238 metrics (or equivalently, with the use of GCP), is analyzed as the “cost of metrics” in our study. Note that
239 the use of metrics influences the emission and temperature pathways and can even affect the feasibility of
240 the temperature target. Thus, we made further assumptions to analyze the cost of metrics as explained in
241 Methods. The methodology described above follows several previous studies (27, 50-52), but there are
242 variations in the methodologies for metric cost calculations, requiring attention when the outcomes are
243 compared. For example, some previous studies (25, 26), using more complex IAMs than the one employed
244 here, used CO₂-equivalent emission targets derived from different metrics, instead of directly constraining
245 the ratios of relevant gas prices, to estimate the costs of using metrics.

246 Previous studies showed that the use of GWP100 does lead to some but not a significant
247 disadvantage in terms of global total abatement costs under stabilization pathways (including small
248 overshoot pathways) (25-28, 50-52). While we confirm this finding (Fig. 3; 1.4% [0.6%, 2.5%] higher global
249 total mitigation costs (till 2200) than the least cost case, with sensitivity ranges in square brackets with
250 respect to different assumptions on the climate sensitivity, the discount rate, and the MAC curves (Methods)),
251 we find that the additional costs of using GWP100 become larger under overshoot than stabilization
252 pathways (e.g. 4.0% [2.5%, 5.5%] under the 1.5 °C high overshoot pathway). The costs of using GWP20 are
253 also higher under overshoot than stabilization pathways (e.g. 10.9% [9.0%, 11.7%] under the 1.5 °C high

254 overshoot pathway). It is worth noting that the use of GWP20, which is sometimes promoted due to concern
255 over the near-term warming (53), yields larger long-term total costs than that of GWP100 under all pathways,
256 including sensitivity cases (Fig. S7, except for the 2 °C stabilization pathway with a discount rate of 6%),
257 reflecting high CH₄ abatement driven by this metric. The use of other time-invariant metrics, in particular
258 GTP100, creates additional costs of over 10% in all cases (Fig. S8, except for those using the discount rate
259 of 2%). For longer time horizons, the use of GWP500 and GTP500 leads to additional costs of over 8 and
260 20%, respectively, under all pathways (Table S2; Figs. S9 and S10). The high costs associated with the use
261 of long time horizon metrics including GTP100 are due to the need for more CO₂ abatement at a higher cost
262 to compensate for CH₄ emissions valued low (27, 28).

263 We further show the “optimal” time horizon for GWP or GTP, which reduces the total mitigation
264 costs as much as possible if implemented throughout the period. We note that a related but different definition
265 of the optimal time horizon is used in ref. (10). We repeated the metric cost calculations by changing the
266 metric time horizon for CH₄ and N₂O between one year and 500 years with a one-year interval (a five-year
267 interval above 150 years). We then identified the optimal time horizon leading to lowest costs under each
268 pathway. The GWP and GTP values for CH₄ and N₂O with a time horizon from one to 500 year(s) were
269 calculated based on Section 8.SM.11 of the IPCC AR5 (for metrics *without* inclusion of climate-carbon
270 feedbacks for non-CO₂). The calculated metric values (Fig. S11) reproduced those reported in Tables 8.A.1
271 and 8.SM.17 of the IPCC AR5. The values of GWPs and GTPs with long time horizons need to be taken
272 cautiously because the uncertainty in metric values increases with time horizon (49, 54).

273 The optimal time horizon depends on the pathways, ranging between 58 [45, 86] and 110 [92, 118]
274 years for GWP and between 29 [25, 34] and 38 [36, 40] years for GTP (Fig. 3). In both metric cases, the
275 longer the period before the stabilization year occurs, the longer the optimal time horizon is. The range is
276 more confined for GTP than for GWP, largely reflecting the different correspondence between time horizons
277 and metric values (Fig. S11). There is however still about 4% additional costs even with the use of the
278 optimal time horizon under the high overshoot pathways (for both GWP and GTP). This finding suggests
279 that, no matter which time horizon is chosen, the use of a single GWP or GTP departs by several percent
280 from cost-effectiveness under overshoot pathways. This arises from the fact that the temporal variations in
281 GCPs under overshoot pathways cannot be well approximated by a single static GWP or GTP. It may be
282 worthwhile to consider the dynamic GTP whose time horizon is kept until the time of stabilization (25, 27)

283 because it captures the rising trend toward the point of stabilization, which can contribute to cost saving. It
284 is known that a dynamic GTP can exceed GCP values under stabilization pathways (12, 38) and may follow
285 the sharp rise in GCP under overshoot pathways. However, we did not analyze it here because it is unclear
286 how to apply a dynamic GTP in the post-stabilization period.

287 The additional costs discussed above may appear rather modest and, indeed, the choice of
288 pathways has a much larger impact on the absolute costs than the choice of metrics (Figs. S9c and S10c).
289 Nevertheless, the choice of metrics strongly influences the cost distributions over time and across gases (with
290 the exception that the impacts on the N₂O abatement costs, emissions, and concentrations are generally
291 insignificant (Figs. S12 to S16)). Previous studies (25, 26, 28) reported significant regional and sectoral
292 impacts from the choice of metrics, despite relatively small global impacts. Our results imply these regional
293 and sectoral variations in cost would be even more significant under overshoot pathways.

294

295 Best available metrics among the IPCC set

296 From a practical perspective, it is useful to interpret our theoretical cost-effective outcome through the eyes
297 of well-established metrics from the IPCC AR5. We thus translated the GCP results (Fig. 2b) in terms of
298 GWPs (or GTPs) with representative time horizons of 20, 50, and 100 years. In other words, we selected
299 “best available GWPs (or GTPs)” from AR5, whose values are most proximate to our GCPs in absolute
300 terms at each point in time, under the assumption that these metric values from the IPCC will not change in
301 the future. In the experiment, we treated GWPs and GTPs separately because these are structurally different.
302 We mainly analyze the results from GWPs, which are predominantly used in policies. The set of metrics
303 from the IPCC was applied for climate impact assessments (55-58) but has not been used for cost-effective
304 mitigation pathways in the way we present.

305 Under the 2 °C stabilization pathway, best available metrics change from GWP100 to GWP50 (or
306 from GTP50 to GTP20) shortly before 2050 (Fig. 4). Under the overshoot pathways, changes in best
307 available metrics are more drastic than under the stabilization pathway, reflecting the larger changes in GCPs
308 with overshoot. Differences in the transitions of best available metrics come from different stabilization
309 years. Another interesting outcome is that GWP100 is chosen from the onset under all pathways, a robust
310 finding except regarding the assumed set of available metrics (Methods; Figs. S17 to S20). If we instead
311 assume six metrics to choose from (i.e. GWP500, GWP200, GWP100, GWP50, GWP20, and GWP10), it

312 chooses GWP500 or GWP200 at the beginning. On the other hand, if we assume just two metrics in the
313 basket of choice (i.e. GWP100 and GWP20), it chooses GWP100 for most of the period under all pathways,
314 except for some periods shortly before the temperature stabilization (Fig. S17).

315 Is it cost-effective to move from a fixed approach permanently using GWP100 to a flexible
316 approach allowing future revisions of the metric time horizon? While the additional costs of *continuously*
317 changing time horizons, like the dynamic GTP, have been investigated previously (25, 27), those of *discretely*
318 changing time horizons, which is arguably more policy relevant, have not been considered before. We show
319 here, for the first time, that it is cost-effective to shift from the fixed to the flexible approach under all
320 pathways, taking also account of their sensitivity cases (Fig. 5; all outcomes, that is, five representative
321 outcomes shown in large circles, as well as sensitivity outcomes expressed as error bars in horizontal and
322 vertical directions, are consistently on the right of the 1:1 line). The cost improvement is larger under
323 overshoot than stabilization pathways. The assumed set of available metrics influence such benefit. Under
324 the 1.5 °C high overshoot pathway (as the most extreme case), choosing from a set of six GWPs instead of
325 the default set of three GWPs reduces the additional costs from 2.3% down to 0.46%. On the other hand,
326 choosing from a set of two GWPs increases the additional costs to 2.5% (but still below 4.0%, the costs of
327 using only GWP100 under this pathway). The assumption on the discount rate has a larger impact on the
328 results than those on the climate sensitivity and the MAC curves – however, the economic benefit for the
329 flexible approach, relative to the permanent use of GWP100, is retained in all cases.

330 We further find that the flexible approach using best available metrics will cost less than *any* fixed
331 approach, including one using the metric with the optimal time horizon. In the former case, the choice is
332 limited to three GWPs but it can be changed at any time. In the latter case, the choice can be any GWP with
333 a time horizon of 1 to 500 year(s) but it cannot be changed with time. Under all pathways including sensitivity
334 cases (a total of 28 cases), the flexible use of best available GWPs is less costly than the fixed use of a single
335 GWP with the optimal time horizon (Fig. 3; Fig. S7). The same finding was obtained from a corresponding
336 experiment using GTPs, except for one case assuming the discount rate of 2% (Fig. 3; Fig. S8). Our results
337 point to a fundamental limit associated with the fixed use of metrics and further support the flexible use of
338 metrics under a range of mitigation pathways.

339

340 **DISCUSSION**

341 Implications for the Paris Agreement implementation

342 Our new findings support the provision of flexibility in the implementation of the Paris Agreement,
343 especially towards metrics with shorter time horizons that can reflect future changes in long-term pathways.
344 We argue that this aspect of mitigation planning could be considered at the recurring global stocktake
345 processes (first in 2023 and then every five years) by including an assessment of the cost-effectiveness of
346 the GHG metric choice. Following the COP24 decision (Decision 19/CMA.1 (20)), the global stocktake
347 serves as a tool for increasing the ambition needed from parties to achieve the goals of the Paris Agreement.
348 The process is supported by a technical assessment to include opportunities for enhanced mitigation action
349 (two sessions in November 2022 and July 2023 for the first global stocktake occurrence; the deadline for
350 materials to be considered in the technical assessment expected to be August 2022). Promoting cost-effective
351 emission abatement is important in this process since it can identify such opportunities and may enable
352 increased ambition levels from parties. Hence, we suggest that an assessment of the cost-effectiveness of
353 GHG metrics for future mitigation strategies could be included as an input to the technical assessment
354 supporting the global stocktake. When deemed necessary, the global stocktake could recommend a revision
355 of the Paris Agreement’s transparency framework to shift towards GWPs with shorter time horizons. We do
356 not know yet the long-term pathway at the time of the upcoming first global stocktake; however, an inclusion
357 of such an agenda item already at the onset of this recurring process could allow the necessary assessments
358 in time to inform subsequent sessions as the long-term pathway unfolds.

359 In fact, a change in metric values is not unprecedented at the UNFCCC. A small revision is already
360 implicit in the COP24 decision to update GWP100 values to those in AR5 (and those in any future IPCC
361 reports), which means that the CH₄ GWP100 will be revised from 21 (SAR) or from 25 (AR4) to 28 (AR5)
362 (or to 34 (AR5), depending on the treatment of climate-carbon feedbacks (59)). But the long-term metric
363 revisions indicated by our analysis are of a different nature and much larger than the proposed update of
364 GWP100 values. This further highlights the need for GWP estimates for different time horizons to be
365 continuously provided by the IPCC, irrespective of scientific advances in other types of metrics.

366 It is important to note that our suggestion is not in conflict with the use of GWP100 in the coming
367 decades. Rather, we argue for a long-term benefit for allowing flexibility in the future choice of metrics,
368 fundamentally because the future pathway is unknown due to the inherent uncertainties in the climate system
369 and the unpredictability of future social, economic, and technological developments; technically because a

370 stabilization year, which is crucial for determining the metric, is not explicitly given in the Paris Agreement
371 text. Even if a 2 and 1.5 °C pathway is followed within this century, and assuming that global cost-
372 effectiveness is an important criterion for guiding international climate policy, the metric would still be time-
373 dependent in response to changing mitigation priorities, particularly under overshoot pathways.

374 We further note on the newly proposed metrics such as GWP* (15), or its variation (60), which
375 can enhance the accuracy of how CO₂ and SLCF emissions are aggregated in terms of the implied warming
376 (18, 61). The GWP* approach in essence compares CO₂ emissions of a certain year with a change in the rate
377 of SLCF emissions over a preceding period (e.g. for 20 years). While such new metrics are intensively
378 debated in recent literature, it is yet unclear to what extent they would require revisions of the Paris
379 Agreement itself to accommodate the need for considering SLCF emissions occurring in preceding decades,
380 if they are applied to the mitigation context that our analysis deals with. Shifting among conventional GWPs
381 with different time horizons seems to be a more practical way of ensuring a cost-effective implementation
382 of the Paris Agreement.

383 Our approach assumes a global actor, without considering the potentially heterogeneous behaviors
384 of individual actors toward time-dependent metrics in the absence of perfect knowledge (62). Nevertheless,
385 cost-effective metrics presented here serve as a useful benchmark, against which more transparent metrics
386 like GWPs can be evaluated. Our cost-effective metrics and the corresponding shifts of GWPs depend on
387 assumptions in the IAM required to calculate future pathways. However, as presented through various
388 sensitivity analyses, the cost advantage for adapting the metric to evolving future was shown to be robust
389 under a broad range of pathways. Our analysis dealt with overshoot pathways more prominently than
390 previous related studies, putting a spotlight on scenarios where the Paris Agreement targets were not
391 achieved due to insufficient near-term climate actions; however, the main conclusion on the advantage of
392 the flexible metric approach is not biased by the choice of pathways and was shown to be valid under all
393 pathways. Our findings suggest that, while the possibility of metric revisions should not impede the political
394 progress toward the Paris Agreement implementation nor disturb market-based mechanisms relying on
395 metrics, there should be room for consideration of metric revisions in the future potentially as part of the
396 global stocktake processes within the UNFCCC. The flexible use of metrics can better serve for a broad
397 range of pathways under uncertain circumstances, including non-ideal overshoot cases.

398

399 **METHODS**

400 Model ACC2

401 ACC2 represents four domains of the global earth system: i) physical climate system, ii) carbon cycle system,
402 iii) atmospheric chemistry system, and iv) economy system. The first three domains are described in the next
403 paragraph and the last one in the paragraph that follows. We keep the model description succinct here, only
404 describing the aspects most pertinent to our present analysis. The current model was developed from earlier
405 simple climate models (63, 64) and produces an equivalent output with the one used in ref. (23). The model
406 (except for the economic module) was cross-compared with other simple climate models under a set of
407 common scenarios (65). The model is written by the General Algebraic Modeling System (GAMS) language.

408 The physical climate system is represented by an energy balance model coupled with a heat
409 diffusion model (22, 66). Radiative forcing agents considered in the model include CO₂, CH₄, N₂O, SF₆, 29
410 species of halocarbons, tropospheric and stratospheric O₃, and stratospheric water vapor. Aerosol forcing is
411 separated by three terms: the direct effect of sulfate aerosols, the direct effect of black carbon and organic
412 aerosols, and the indirect effects of all aerosols. The CH₄ lifetime is influenced by OH, NO_x, CO, and VOC.
413 Note that each forcing term is calculated separately without any gas aggregation using metrics like GWP100.
414 The global carbon cycle is provided by a box model: four boxes for the coupled atmosphere-ocean and
415 another four for the land. Saturation of ocean CO₂ uptake under rising atmospheric CO₂ concentrations is
416 modeled through the thermodynamic equilibrium of carbonate species in the ocean (67, 68). The CO₂
417 fertilization of the land biosphere is parameterized by a commonly used β factor. No climate-carbon
418 feedbacks are assumed in our analysis; that is, carbon cycle processes are assumed to be insensitive to the
419 temperature change. The equilibrium climate sensitivity is fixed at 3 °C, within the 1.5 – 4.5 °C range
420 suggested by the IPCC AR5 (in the Thematic Focus Elements 6). Other uncertain parameters such as those
421 related to aerosol forcing and CO₂ fertilization are optimized based on a Bayesian approach using historical
422 observations such as global-mean temperature changes and atmospheric CO₂ concentrations (69). The
423 interdependencies among the parameter estimates are considered, including the one between the climate
424 sensitivity and the aerosol forcing strength (70). The optimization is performed by using the CONOPT3, a
425 nonlinear optimization solver provided with GAMS.

426 The economy module is used to estimate the costs of mitigating CO₂ (fossil fuel origin), CH₄, and
427 N₂O emissions based on a first-order method using global MAC curves (38, 45) (Fig. S2). The MAC curves

428 are assumed time-invariant and given as a function of the abatement level (in percent) of the respective gas
429 relative to an assumed baseline level (i.e. the International Institute for Applied Systems Analysis (IIASA)
430 Greenhouse Gas Initiative (GGI) A2r baseline scenario (71)). The fossil fuel CO₂ MAC curve is based on
431 the output of the GET energy system model (45), which was simulated iteratively under different future
432 trajectories of the carbon price. Although the carbon price for a given level of emission reductions should be
433 time-dependent, we use a mathematical function to approximate the data collected from 2060 to 2100 and
434 apply it as the MAC function throughout the period in our analysis. Limitations associated with the fixed
435 MAC curve approach are partially but imperfectly mitigated by the constraints on the temporal changes in
436 the abatement level to account for the technological change and socioeconomic inertia associated with
437 emission abatement. Namely, the rate of change in the abatement level (i.e. first derivative) is kept below
438 4% per year for all three gases, implying a limit for the technological change; furthermore, the rate of
439 abatement change (i.e. second derivative) is below 0.4% per year, mimicking socioeconomic inertia. These
440 first- and second-derivative constraints limit the extent of the MAC curves that can be used in the near term.
441 The implication of these constraints is that, if the abatement starts in 2020, the abatement level can reach up
442 to 20% in 2030, 60% in 2040, and 100% in 2050 (i.e. zero emissions from fossil fuel CO₂). These constraints
443 allow larger changes in the abatement level than those found in the 450 ppm CO₂eq scenarios in the AR5
444 database (Supplementary Figs. 12 to 14 of ref (23)). The maximum abatement levels for CO₂ (fossil fuel
445 origin), CH₄, and N₂O are assumed at 112%, 70%, and 50%, respectively. The abatement potential for CO₂
446 can exceed 100% primarily because the IAM, on which our CO₂ MAC curve is based, considers bioenergy
447 combined with carbon capture and storage as an option in the mitigation portfolio (45). Such deep mitigation
448 could impact biodiversity and food security through land-use changes associated with large-scale negative
449 emissions in a way that may not be acceptable in the real world (72-74), especially if large scale low diversity
450 forest plantations and bioenergy crops coupled to capture and storage are the negative emissions technologies
451 being preferentially adopted in the mid to late century. Other political and governance constraints, which can
452 be also important in the real world, are not considered in our model. Our approach is kept simple and works
453 under the assumption that CO₂ and non-CO₂ mitigation measures are interchangeable, which is partially true
454 given the necessity to finance mitigation actions but may also break down for measures involving co-
455 reduction of GHGs. Our MAC curve approach does not capture GHG abatement measures entailing net
456 negative costs that have however not been implemented due to non-economic factors. The emissions of all

457 other gases and pollutants including CO₂ from land use change are prescribed without cost calculations (i.e.
458 GGI A2r 480 ppm CO₂eq stabilization). The discount rate is assumed at 4% by default. We analyze the
459 pathway until 2200, going beyond the 2100 time frame commonly analyzed. The long time frame is required
460 to capture overshoot pathways under which temperatures will not return to 2 °C or lower during this century.

461

462 Pathways and metric costs

463 The stabilization and overshoot pathways were derived from the cost-effective calculation method described
464 above. We let the model to determine the abatement levels of three gases over time under the abatement
465 constraints (i.e. first- and second-derivative constraints as well as the upper limits of abatement levels) to
466 arrive at a pathway that meets a policy objective while minimizing the global total costs of mitigation. Two
467 temperature target levels (2 °C and 1.5 °C) and three temperature pathway profiles (non-overshoot, medium
468 overshoot (till 2100), and high overshoot (till 2150)) were considered. Temperature overshoot emerges as a
469 consequence of how the temperature target is implemented: the target is assumed effective only after a certain
470 point in time in the future.

471 It should be noted that the reference pathways against which the additional costs of using metrics
472 were calculated are not identical to the illustrative pathways in Fig. 2. All metric cost calculations in our
473 study did not use the abatement constraints, that is, the first- and second-derivative constraints as well as the
474 upper limits of abatement levels, which were used to derive the illustrative pathways. These constraints
475 influence the metric cost calculations and in some cases make the pathway infeasible because they can be
476 too restrictive when applied together with metrics. In order to keep consistency, the abatement constraints
477 were also not used in the reference pathways to derive the cost of metrics. However, the overall pathways
478 and mitigation costs without the use of abatement constraints are not substantially different from those with
479 the use of such constraints, except for cases with high overshoot. Another exception is the periods when the
480 mitigation starts and when the target is met (Table S2; Figs. S12 to S16). In such periods, particularly under
481 the overshoot pathways, abatement levels can change drastically in the absence of the abatement constraints,
482 requiring careful interpretation.

483

484 Sensitivity analysis

485 We consider the following three sources of uncertainty: equilibrium climate sensitivity, discount rate, and

486 MAC curves. The equilibrium climate sensitivity is assumed to be 3 °C by default, with sensitivity cases of
487 2 °C and 4.5 °C. In comparison to the 1.5 – 4.5 °C range, the uncertainty in equilibrium climate sensitivity
488 indicated by the IPCC AR5, our analysis did not consider climate sensitivity below 2 °C as suggested by a
489 previous study using ACC2 (69) and recent lines of evidences (75, 76). The discount rate is set at 4% by
490 default and assumed at 2% and 6% in sensitivity cases, spanning a typical range considered in cost-
491 effectiveness analyses (i.e. 5 to 6% in line with market interest rates), as well as low discount rates suggested
492 by recent literature (77). The uncertainty in MAC curves is generally large and a related study reports an
493 uncertainty range of $\pm 50\%$ in the MAC curves (52). We consider two cases changing the priority of CO₂ and
494 non-CO₂ mitigation alternately: one case assuming a 50% higher CO₂ MAC curve and 50% lower CH₄ and
495 N₂O MAC curves and the opposite case assuming a 50% lower CO₂ MAC curve and 50% higher CH₄ and
496 N₂O MAC curves. Note that we vary the assumption on the N₂O MAC curve for consistency, but this has
497 little influence on the overall results. In the sensitivity analysis, we vary the assumptions on these
498 uncertainties just one by one from the default and do not vary more than one assumption at a time due to the
499 computational burden, yielding a total of seven cases including the default case. A larger number of sources
500 of uncertainty were considered in the historical inversion of the physical part of the model. But in the metric
501 cost analysis demanding more computational resource, we focus on the equilibrium climate sensitivity, as
502 the most important uncertain parameter in the physical earth system, while acknowledging that other
503 parameters, including those related to climate-carbon cycle feedbacks, can also be important. Note that, with
504 the climate sensitivity of 4.5 °C, the 2 °C stabilization pathway and the 1.5 °C medium overshoot pathway
505 are not feasible with the abatement constraints put in place. As a result, these two pathways are not
506 considered also in the metric cost analysis when the climate sensitivity is set at 4.5 °C, even though these
507 pathways are feasible without the abatement constraints. The largest climate sensitivity that makes these
508 target pathways feasible are 3.4 °C in both cases.

509 In the analysis of best available metrics, we further consider the sensitivity of the assumed set of
510 available metrics. The default set of time horizons considered for GWP and GTP are 100, 50, and 20 years.
511 As a comparison, the IPCC AR5 lists the values of GWP20, GWP100, GTP20, GTP50, and GTP100 for a
512 number of climate forcers in Table 8.A.1. AR5 also reports GWPs and GTPs with a time horizon of 100, 50,
513 20, and 10 years for a limited number of climate forcers in Table 8.SM.17. In contrast, the previous IPCC
514 Assessment Reports up to AR4 present the values of GWPs with a time horizon of 500, 100, 20 years (GTP

515 values are only in AR5). We consider the following alternative sets of available time horizons for GWP and
516 GTP: two time horizons (100 and 20 years) and six time horizons (500, 200, 100, 50, 20, and 10 years). In
517 the sensitivity analysis, we choose a time horizon from two or six available time horizons, the CH₄ GWP (or
518 GTP) of which is closest to the GCP at each point in time. The chosen time horizon is also be used for N₂O
519 GWP (or GTP) as done in the default analysis. In this exercise, we refer to the AR5 metric values *without*
520 inclusion of climate-carbon feedbacks for non-CO₂ gases. Note that same metric values are assumed in the
521 future period in our analysis. The IPCC metric values have in fact changed over the assessment cycles due
522 to several compounding and competing factors, including improvement in scientific understanding and
523 changing background atmospheric conditions (Section 8.7.2.1 of the IPCC AR5). The metric values will
524 probably be revised also in the future, but such changes are impossible to predict.

525

526 Scenarios obtained from the IPCC SR15

527 Data for the temperature pathways considered by SR15 were downloaded from the Integrated Assessment
528 Modeling Consortium (IAMC) 1.5 °C Scenario Explorer hosted by IIASA (48). The following five classes
529 of pathways are considered in SR15: Below-1.5°C, 1.5°C-low-OS, 1.5°C-high-OS, Lower-2°C, and Higher-
530 2°C (Table 2.1 of the IPCC SR15). Out of 222 scenarios in the five classes, 92 temperature pathways are
531 available from the Scenario Explorer website for download (accessed on 8 February 2019). Most of them
532 are given for the period 2005–2100 with five or ten-year intervals. There are two temperature pathways
533 indicating temperatures significantly higher than 2°C during this century (one peaking at 2.3 °C in 2080 and
534 the other at 2.66 °C in 2090), which were removed from our analysis. Temperature data in SR15 use the
535 1850-1900 mean temperature as a reference. The 1850-1900 mean temperature in our model is 0.0294 °C
536 based on the inverse calculation (22, 69). Thus, the SR15 temperature pathways shown in Fig. 2 are adjusted
537 accordingly to account for the difference in the base temperature.

538

539 **SUPPLEMENTARY MATERIALS**

540 Supplementary Materials are available for this paper and include Figs. S1 to S20 and Tables S1 and S2.

541

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713

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728 **Author contributions**

729 K.T. and O.B. conceived this study. K.T. led the study. K.T., O.B., P.C. and D.J.A.J. designed the experiment.
730 K.T. performed the analysis. K.T., O.B., P.C., D.J.A.J., and J.M. analyzed the results. K.T. drafted the
731 manuscript, with contributions from all co-authors.

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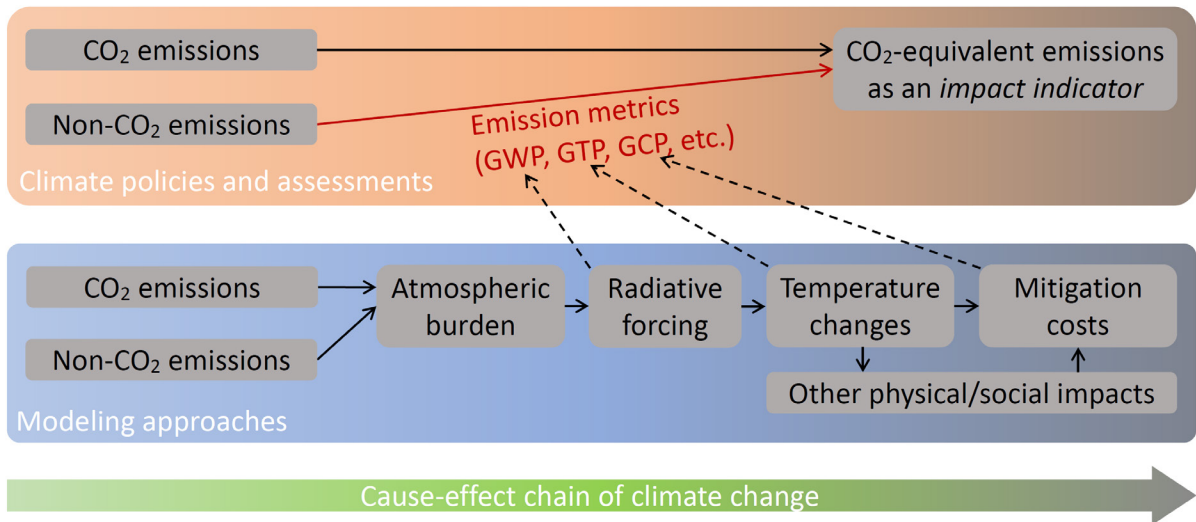
733 **Competing interests**

734 The authors declare no competing financial interests.

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736 **Data and materials availability**

737 All data needed to evaluate the conclusions in the paper are present in the paper and the Supplementary
738 Materials. Correspondence and requests for materials should be addressed to K.T.



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741 **Fig. 1. The use of greenhouse gas emission metrics in climate policies and assessments and its relations**

742 **to modeling approaches.** The figure shows our interpretation that climate policies and assessments (orange-

743 to-grey area) regard CO₂-equivalent emissions as a surrogate indicator of climate impacts, while modeling

744 approaches (blue-to-grey area) look more directly into the temperature change and other physical and social

745 impacts as an indicator of climate impacts. Grey boxes show factors, such as emissions and temperature

746 change, along the cause-effect chain of climate change from left to right (green-to-grey bar), following Fig.

747 8.27 of the IPCC AR5. Solid arrows represent cause-effect relationships between such factors. The arrow

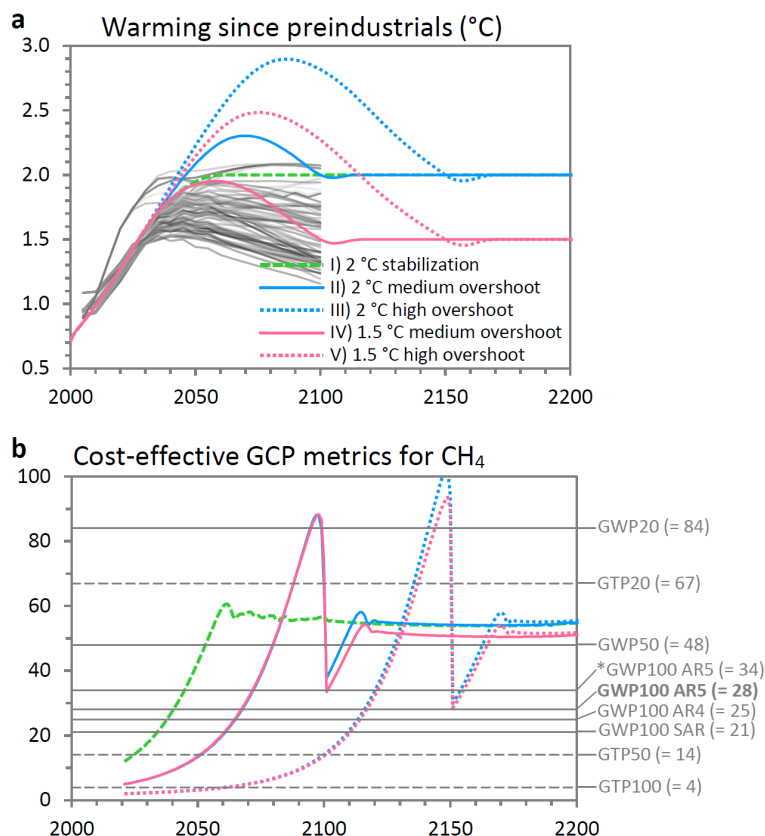
748 where emission metrics are applied is highlighted in red. If GWP is used, the conversion from non-CO₂

749 emissions to CO₂-equivalent emissions implicitly uses radiative forcing calculations using models (dashed

750 arrow). Likewise, if GTP and GCP are used, the CO₂-equivalent conversion relies on temperature and

751 mitigation cost calculations using models, respectively (dashed arrows). For the purpose of clarity, only first-

752 order relationships are shown. Temporal and spatial aspects are suppressed in the figure.



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754

755 **Fig. 2. Temperature stabilization and overshoot pathways and cost-effective GCP metrics for CH₄. In**

756 panel **a**, dashed green lines show the case in which the 2 °C target is achieved without overshoot. Blue and

757 pink lines indicate the cases in which the temperature stabilizes at the 2 and 1.5 °C warming levels after

758 overshoot, respectively. Solid and dotted lines correspond to cases where overshoot is assumed unavoidable

759 before 2100 and 2150, respectively (termed “medium” and “high” overshoot, respectively, in reference to

760 “low” overshoot considered in the IPCC SR15). Grey lines in the background indicate the range of

761 temperature pathways considered in SR15 (Methods). In panel **b**, the CH₄ GCPs under the five pathways

762 (line designations as in panel **a**) are shown. GWPs and GTPs with the time horizons of 20, 50, and 100 years

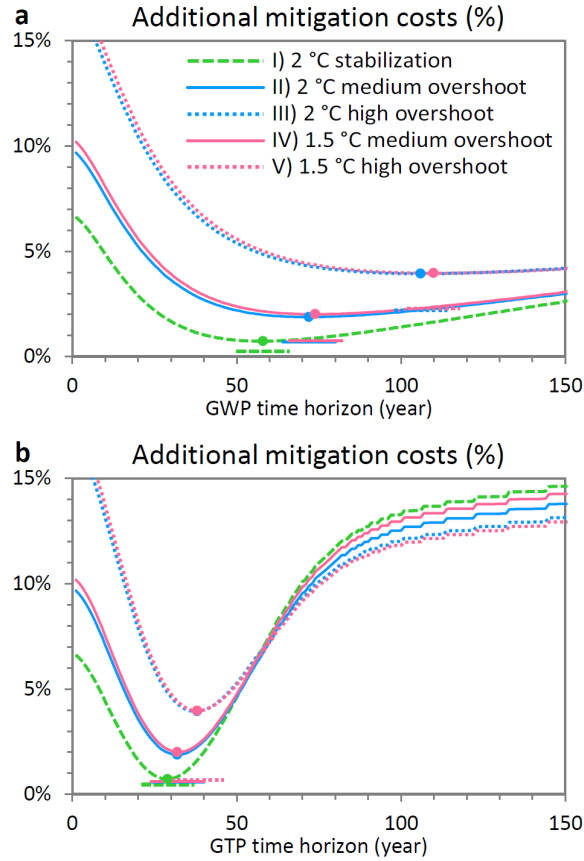
763 are shown in solid and dashed grey lines, respectively, as a reference for comparison. The metric values

764 indicated in parentheses are taken from Tables 8.A.1 and 8.SM.17 of the IPCC AR5 (i.e. those *without*

765 inclusion of climate-carbon feedbacks for non-CO₂), unless noted otherwise. For GWP100, the panel shows

766 four different values including those from earlier IPCC Assessment Reports. The GWP100 value in AR5

767 *with* inclusion of climate-carbon feedbacks for non-CO₂ is indicated by * and taken from Table 8.7 of AR5.



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769

770 **Fig. 3. Additional mitigation costs of using GWP and GTP with a range of time horizons under the**

771 **stabilization and overshoot pathways.** The additional mitigation costs (in percent) with the use of GWP

772 and GTP relative to the lowest costs without the use of metrics (or equivalently, with the use of GCP) are

773 shown in panels **a** and **b**, respectively. The results with the time horizons between one and 150 year(s) are

774 presented. The minimum under each pathway, which is marked by a filled circle, indicates the optimal time

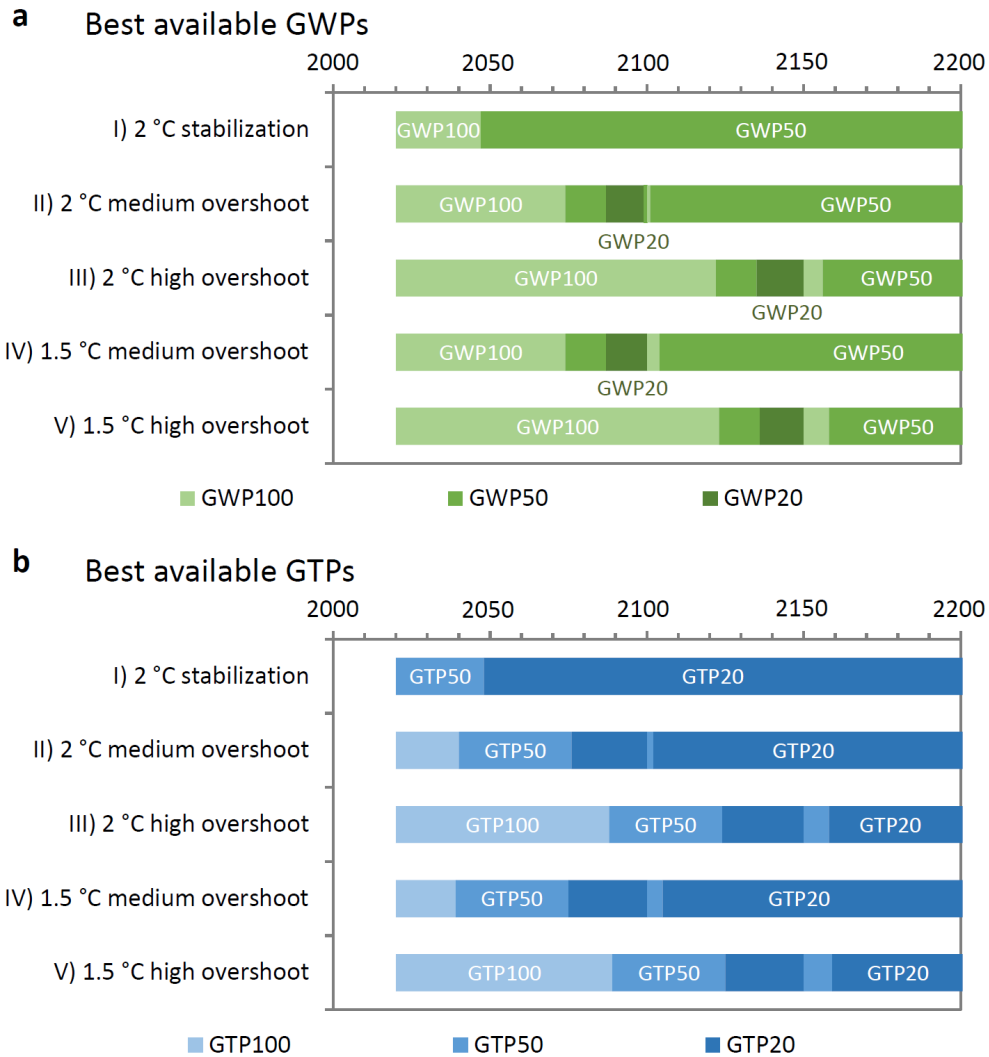
775 horizon and the residual additional mitigation costs. The short horizontal bars vertically aligned with each

776 minimum point indicates the additional mitigation costs of using best available GWPs (from the default set

777 of three metrics GWP100, GWP50, and GWP20) (panel **a**) or best available GTPs (from the default set of

778 GTP100, GTP50, and GTP20) (panel **b**) under each pathway. All horizontal bars follow the legend in panel

779 **a.**



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781

782 **Fig. 4. Choices of representative GWPs and GTPs most proximate to cost-effective GCP metrics under**

783 **the stabilization and overshoot pathways.** GWPs and GTPs with three representative time horizons (i.e.

784 20, 50, and 100 years) from the IPCC AR5 are considered. One of the three GWPs and GTPs (in panels **a**

785 and **b**, respectively), whose value is closest to the corresponding GCP in absolute terms, is shown under each

786 pathway. The color is designated according to the time horizon as indicated in the legend at the bottom of

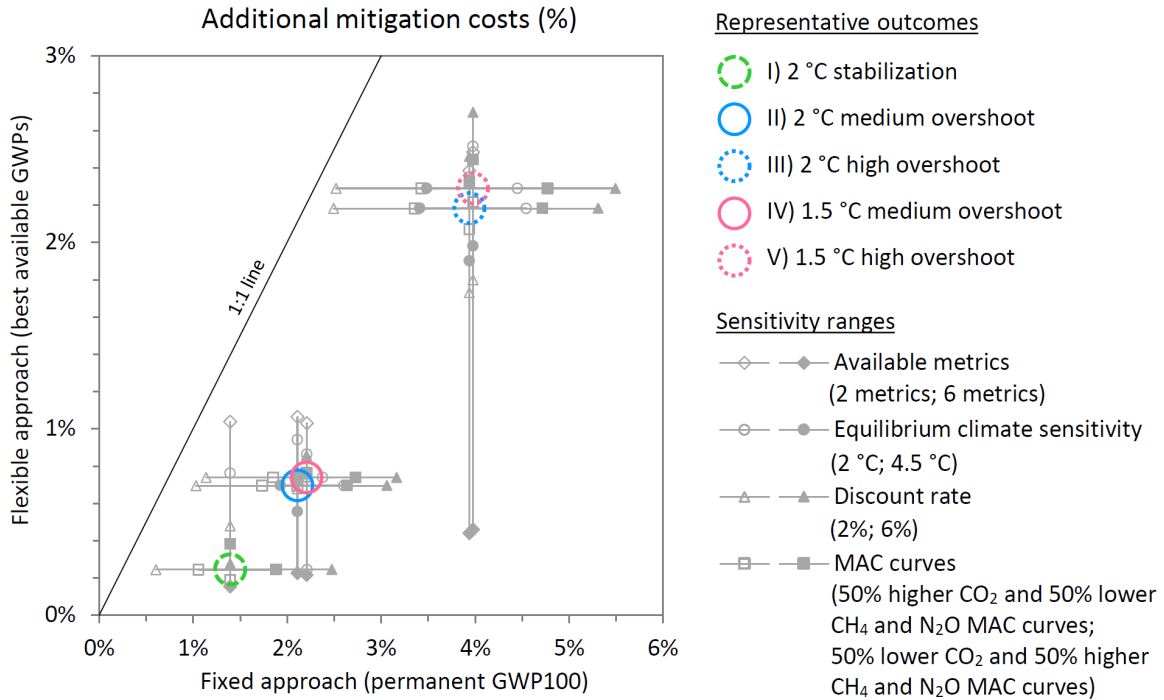
787 each panel. On the basis of ref. (78), we refer to the IPCC metric values *without* inclusion of climate-carbon

788 feedbacks for non-CO₂ gases (Tables 8.A.1 and 8.SM.17 of the IPCC AR5), while noting that it is unclear

789 whether the COP24 decision (paragraph 37 of the Annex to Decision 18/CMA.1 (20)) refers to metric values

790 with or without inclusion of climate-carbon feedbacks for non-CO₂ gases. It should also be noted that the

791 IPCC AR5 does not endorse any metrics assessed.



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Fig. 5. Additional mitigation costs of shifting from the permanent use of GWP100 to the more flexible use of GWPs. This scatter plot shows the additional mitigation costs (in percent) with the permanent use of GWP100 (x-axis) versus those with the use of best available GWPs (y-axis), both relative to the lowest costs without the use of metrics (or equivalently, with the use of GCP). The 1:1 line is indicated in black. The outcomes under default assumptions are indicated in large color circles as representative outcomes. The sensitivity ranges are shown in both horizontal and vertical directions and characterized by categories. In the default set of assumptions, the number of available metrics (or time horizons) is three (i.e. GWP100, GWP50, and GWP20), the equilibrium climate sensitivity is 3 °C, and the discount rate is 4%. The assumptions in the sensitivity cases are indicated in parentheses in the legend. Note that horizontal error bars indicate their respective sensitivity ranges only for the fixed approach. The same goes for vertical error bars indicating sensitivity ranges only for the flexible approach. By definition, sensitivity ranges with respect to the number of available metrics appear only to the vertical direction. Note also that the 2 °C stabilization pathway and the 1.5 °C medium overshoot pathway are not considered in the case of 4.5 °C climate sensitivity since these pathways are infeasible with the high climate sensitivity.