



Substantial reductions in non-CO₂ greenhouse gas emissions reductions implied by IPCC estimates of the remaining carbon budget

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Carbon budgets are quantifications of the total amount of carbon dioxide that can ever be emitted while keeping global warming below specific temperature limits. However, estimates of these budgets for limiting warming to 1.5 °C and well-below 2 °C include assumptions about how much warming can be expected from non-CO₂ emissions. Here, we uncover the non-CO₂ emissions assumptions that underlie the latest remaining carbon budget estimates by the Intergovernmental Panel on Climate Change and quantify the implication of the world pursuing alternative higher or lower emissions. We consider contributions of methane, nitrous oxide, fluorinated gases, and aerosols and show how pursuing inadequate methane emission reductions causes remaining carbon budgets compatible with the Paris Agreement temperature limits to be exhausted today, effectively putting achievement of the Paris Agreement out of reach.

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The remaining carbon budget (RCB) is an estimate of the total net amount of carbon dioxide (CO₂) that can still be emitted while keeping global warming to below a specified temperature threshold^{1,2}. Estimating these budgets requires the combination of a set of at least five influencing factors^{2–4} including: the current level of anthropogenic global warming; the expected warming per unit of CO₂ emitted (known as the transient climate response to cumulative emissions of CO₂, or TCRE); an estimate of how global warming evolves once global CO₂ emissions are reduced to zero (known as the zero CO₂ emissions commitment⁵, or ZEC); an adjustment for Earth system feedbacks that would otherwise not be captured; and finally, an estimate of how much non-CO₂ emissions will contribute to warming in the future compared to today. The latter requires assumptions both about future non-CO₂ emission levels and about their warming effect. Past studies have looked at the assumptions and impact of short-lived climate forcers⁶, carbon-cycle and other uncertainties⁷, climate policy choices⁸ and energy system transformations⁹ on the RCB¹⁰. Here, we uncover the broader non-CO₂ emissions assumptions that underlie some of the most prominent RCB estimates that are currently available in the literature, and show how shortfalls in mitigation ambition for methane (CH₄) and nitrous oxide (N₂O) put achievement of the Paris Agreement targets out of reach.

The sixth assessment report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) presents the latest authoritative assessment of the RCB³, with more recent studies updating this quantification using identical methods and more recent data¹¹. These RCB estimates apply the framework established in the context of the IPCC Special Report on Global Warming of 1.5 °C^{2,12} which requires the contributions of non-CO₂ emissions to be explicitly estimated. They use internally consistent mitigation scenarios to extract relationships between peak warming and the additional warming caused by non-CO₂ emissions, including from non-CO₂ greenhouse gas and aerosol emissions. In particular, these estimates use community scenario databases that reflect the broader mitigation scenario literature and which have been compiled regularly over the past years as part of the IPCC assessment process^{13–15}. The future warming contribution of non-CO₂ emissions as a function of peak total anthropogenic

warming is estimated with reduced-complexity climate models calibrated to the IPCC's physical science assessment^{16,17}. The difference between estimated future and current non-CO₂ warming is then used to determine the remaining allowable warming for CO₂ (and hence for the RCB) until a specified warming limit is reached.

This approach^{2,3,12} allows us to present RCB estimates that apply to CO₂ only while being consistent with non-CO₂ emissions evolutions in line with a global net-zero transition and achievement of the Paris Agreement goals. This co-dependence of RCB estimates on non-CO₂ emissions should be an integral part of the communication of RCBs. For example, the IPCC highlights that RCB estimates in line with holding warming in the range of 1.5–2 °C can vary by 220 GtCO₂ depending on the strength of concurrent non-CO₂ reductions³. However, often lost in the communication of RCBs is the notion that all estimates assume stringent non-CO₂ mitigation, and that the 220 GtCO₂ variation represents the variation across different stringent non-CO₂ mitigation futures in line with the Paris Agreement. Another approach explored in the literature is to express all non-CO₂ emissions as CO₂-forcing-equivalent emissions and consider them as part of a total CO₂-forcing-equivalent budget¹⁸. The latter approach provides an alternative way forward, but does not allow us to easily understand the non-CO₂ contributions in terms of reductions of other main greenhouse gases such as methane. To clarify the non-CO₂ mitigation implied in RCB estimates, we here uncover the non-CO₂ reductions and estimate the consequences of a shortfall in non-CO₂ mitigation ambition.

Results

Starting from the latest IPCC compilation of internally consistent mitigation scenarios¹⁵ we estimate RCBs as in IPCC AR6^{3,11} (see Supplementary Tables S1 and S2) and present the accompanying non-CO₂ assumptions. RCB estimates require deep reductions in non-CO₂ greenhouse gases (Table 1). RCB estimates in line with limiting warming to 1.5 °C assume 1.5 °C-compatible CH₄ reductions from 2020 to 2050 of 51% (47–60%, range between 25th and 75th quantile regressions at 1.5 °C of global warming across scenarios, see Fig. 1, panel a). These reductions change to 44% (39–53%) and 34% (27–43%) for RCBs in line with limiting

Table 1 Non-CO₂ emissions reductions in 2050 relative to 2020, and implied CO₂-warming-equivalent emissions underpinning IPCC and other remaining carbon budget estimates.

Warming limit relative to 1850–1900	Percentile	Emissions change in 2050 relative to 2020 [%]							Implied cumulative CO ₂ warming equivalent emissions between 2020 and 2050 [GtCO ₂ -we]				
		CH ₄	CH ₄ AFOLU	CH ₄ non-AFOLU	N ₂ O	F-gases	SO ₂	BC	CH ₄	CH ₄ AFOLU	CH ₄ non-AFOLU	N ₂ O	F-gases
1.5 °C	10%	–69	–52	–86	–47	–98	–80	–77	–440	–107	–335	67	11
	25%	–60	–43	–80	–35	–98	–78	–57	–339	–72	–317	72	13
	50%	–51	–32	–73	–22	–91	–78	–53	–275	–25	–264	81	25
	75%	–47	–16	–67	–7	–47	–74	–49	–225	37	–210	87	38
	90%	–39	–6	–57	2	–35	–66	–45	–135	64	–183	92	46
1.7 °C	10%	–62	–47	–77	–42	–91	–78	–76	–376	–88	–294	69	14
	25%	–53	–38	–71	–30	–85	–76	–57	–281	–55	–274	74	18
	50%	–44	–27	–64	–18	–75	–73	–52	–215	–10	–220	83	30
	75%	–39	–12	–58	–3	–33	–68	–46	–161	53	–164	89	43
2.0 °C	90%	–31	–1	–48	6	–20	–60	–42	–74	82	–134	94	50
	10%	–51	–39	–64	–35	–81	–75	–76	–280	–60	–234	73	19
	25%	–43	–30	–58	–23	–66	–72	–55	–193	–29	–208	78	26
	50%	–34	–21	–51	–11	–50	–66	–49	–124	13	–154	86	38
	75%	–27	–4	–44	2	–12	–59	–41	–66	77	–94	92	49
90%	–20	6	–33	12	3	–51	–36	17	109	–62	98	56	

Estimates are provided for global CH₄ emissions, CH₄ from agriculture, forestry and other land use (AFOLU), non-AFOLU CH₄ emissions, and global N₂O emissions, and fluorinated gases (F-gases), as well for the aerosol and aerosol precursors SO₂ and black carbon (BC).

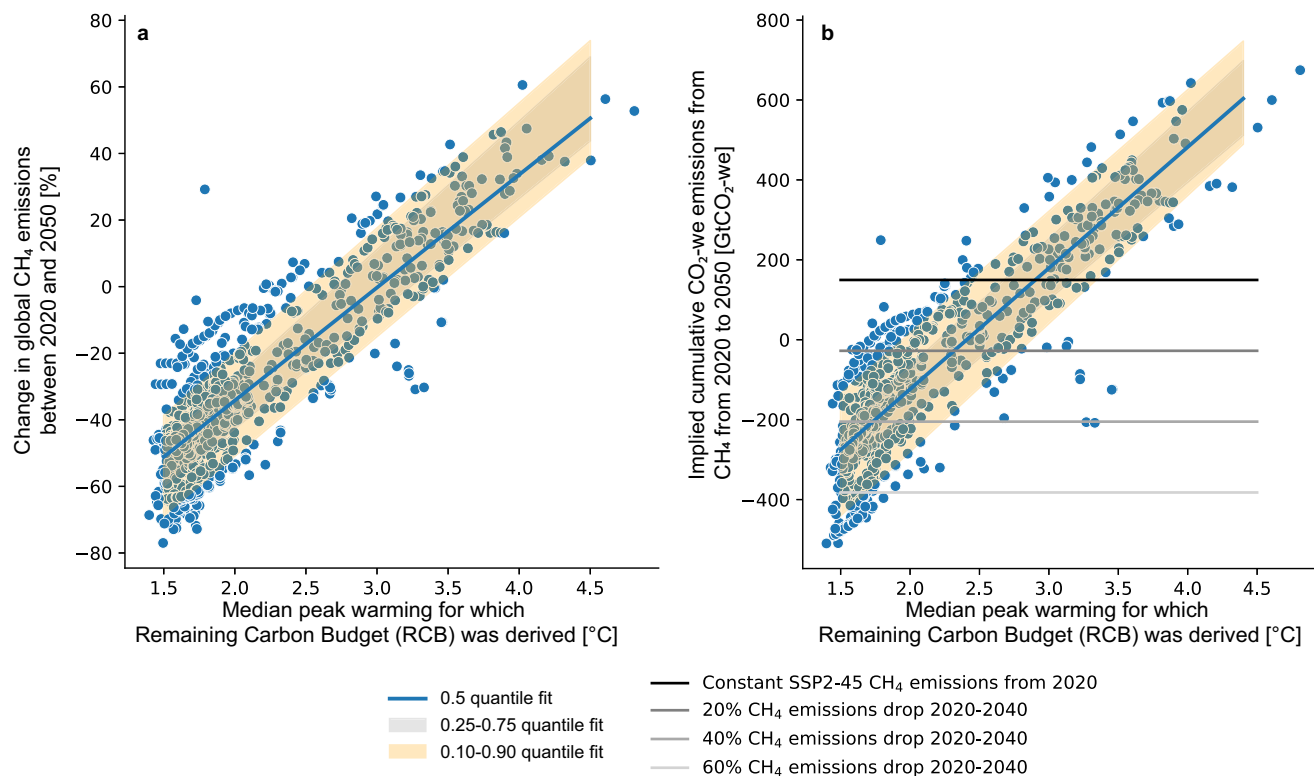


Fig. 1 Global methane (CH₄) emissions reductions and their CO₂-warming-equivalent (CO₂-we) contributions compatible with remaining carbon budget estimates (RCBs) limiting warming to specific peak temperature levels. a Change in global CH₄ emissions between 2020 and 2050 as a function of the peak warming limit for which an RCB is estimated; **b** CO₂-we emissions contribution of global CH₄ emissions between 2020 and 2050 as assumed in RCB estimates, as a function of the peak warming limit for which an RCB is estimated. Each dot in both panels represent the characteristics of one emissions scenario as available in the IPCC AR6 scenario database¹⁵. Horizontal lines in panel (b) show values for stylized global CH₄ emissions reductions between 2020 and 2050. Plots for other sectors or other non-CO₂ species are included in Supplementary Figs. S2–10.

warming to 1.7 °C and 2.0 °C, respectively. Global N₂O emissions are also limited, with a reduction of 22% (7–35%) between 2020 and 2050 for 1.5 °C-compatible RCBs, and reductions of 18% (3–30%) and 11% (1% increase–23%) for 1.7 °C and 2 °C-compatible RCBs, respectively. In all cases, these CH₄ and N₂O reductions represent marked global emission reduction efforts. An illustration of the non-CO₂ emission timeseries is provided in Supplementary Fig. S1. Compatible reductions by the years 2030 and 2040 are provided in Supplementary Tables S3 and S4, respectively.

The agricultural sector, including dairy and cattle farming, is a key source of non-CO₂ greenhouse gas emissions globally¹⁹. Because of the distinct mitigation potential profile for agriculture²⁰, we also look at the specific non-CO₂ greenhouse assumptions for this sector. Global N₂O emissions are dominated by the agricultural sector¹⁹. Emissions reductions mentioned above for total N₂O emissions are therefore also applicable to agricultural N₂O emissions. For methane, the reduction percentages over the 2020–2050 period differ across sectors, because the CH₄ mitigation potential in the agricultural is very different from the potential in the fossil-fuelled energy sector²¹. Agricultural CH₄ emissions are assumed to reduce by 32% (16–43%) in the estimation of 1.5 °C-compatible RCBs, and by 27% (12–38%) and 21% (4–30%) for 1.7 °C and 2 °C-compatible RCBs, respectively. In the same way, this means that RCB-compatible CH₄ reductions from the fossil-fuel sector have to be deeper than the global total CH₄ emissions reductions. IPCC RCB estimates for 1.5 °C imply compatible fossil-fuel CH₄ emissions reductions of 73% (67–80%) in 2050 relative to 2020, and 64% (58–71%) and 51% (44–58%) for being compatible with 1.7 °C and 2 °C, respectively.

Fluorinated gases are not only controlled by the United Nations Framework Convention on Climate Change but also by the Kigali Amendment to the Montreal Protocol on Substances That Deplete the Ozone Layer. Here, we look at the assumed reductions in aggregated hydrofluorocarbons (HFCs) and per-fluorinated compounds (PFCs). IPCC RCB estimates for 1.5 °C imply compatible aggregated F-gas emissions reductions of 91% (47–98%) in 2050 relative to 2020, and 75% (33–85%) and 50% (12–66%) for being compatible with 1.7 °C and 2 °C, respectively.

A last set of non-CO₂ emissions that is often overlooked are aerosol (and their precursors) such as black carbon (BC) or SO₂ emissions, which are also air pollutants. These short-lived species are co-emitted with CO₂ through combustion processes, and are therefore projected to strongly decrease in low-emission scenarios²². Air pollution control policies can drive additional reductions²³. This large degree of co-control of key air pollutants through CO₂ emission reductions is important as at present these short-lived air pollutants are estimated to cause a net cooling^{24,25}. As their atmospheric abundance declines, the disappearance of this cooling effect and the unmasking of the underlying greenhouse gas warming must be accounted for in RCB estimates. Estimates by the IPCC do so by including internally consistent evolutions of these species in their calculations^{2,3,11,12}. Table 1 shows how RCB estimates compatible with 1.5 °C already account for a reduction in global SO₂ emissions of 78% (74–78%) between 2020 and 2050, with RCBs for 1.7 °C and 2 °C assuming reductions of 73% (68–76%) and 66% (59–72%), respectively. Assumed median BC reductions between 2020 and 2050 are similar across the various stringent levels of warming assessed here, at around 49–53%.

Discussion

With the non-CO₂ emission reduction assumptions included in RCB estimates unveiled, we now turn to quantifying the impact of alternative assumptions, a lack of mitigation ambition, or mitigation failure of non-CO₂ emissions. To this end, we estimate the CO₂-warming-equivalent (CO₂-we) emissions²⁶ implied by the median non-CO₂ greenhouse gas reductions assumed in RCB estimates. These CO₂-we emissions represent the internally consistent non-CO₂ changes that were included when estimating global RCBs. They also provide a direct way of quantifying the RCB impact of alternative assumptions.

Global CO₂-we contributions to RCBs between 2020 and 2050 for CH₄ are −275, −215, and −124 GtCO₂-we for RCBs compatible with limiting warming to 1.5 °C, 1.7 °C and 2.0 °C, respectively (Table 1). The interquartile range around these numbers is relatively stable across the warming levels assessed here at around ±50–75 GtCO₂-we (Fig. 1b). These central estimates allow the direct estimation of the RCB impact of alternative CH₄ evolutions over the next decade. Assuming global CH₄ emissions do not decline but instead are kept constant at 2020 levels would reduce the RCB by 431, 370, and 280 GtCO₂-we for RCBs compatible with 1.5 °C, 1.7 °C, and 2 °C, respectively. In other words, choosing not to reduce CH₄ emissions and correctly adjusting for this decision in RCB estimates would cause 1.5 °C-compatible RCBs to be exhausted as of today (Fig. 1b, Table 1, Supplementary Tables S2, S5), in effect putting the 1.5 °C ambition of the Paris Agreement out of reach. Even a global 40% reduction between 2020 and 2040 would cause a 1.5 °C-compatible RCB reduction of about 60 GtCO₂-we, highlighting the importance of deep reductions in CH₄. Similar adjustments can be estimated for alternative reductions of the split-up agricultural and non-agricultural CH₄ emissions and for N₂O (Supplementary Table S5).

Conclusions

In conclusion, when global RCB estimates from the IPCC or more recent derivatives are used^{3,11} (see Supplementary Tables S1 and S2) the here reported median CO₂-we emissions are to be considered as the internally consistent contributions from non-CO₂ emissions. Any deviations from this median assumption for non-CO₂ contributions will have to be taken into account by adequately adjusting the assumed RCB estimate. These adjustments can result in an important increase or decrease of the global RCB, depending on whether the median assumption is over- or underachieved. Importantly, a failure to reduce global agricultural CH₄ and N₂O emissions over the next decades will put the achievement of the Paris Agreement out of reach.

Methods

Remaining carbon budget (RCB) calculations follow the method described in refs. ^{2,3,12} and documented in ref. ²⁷ with updates as described in ref. ¹¹.

Non-CO₂ contributions are based on and estimated from the ensemble of mitigation scenarios compiled in the context of the IPCC Sixth Assessment Report¹⁵. Consistent with the scenario versions used in the IPCC RCB estimations, this analysis only uses emissions timeseries from scenarios if they were available in the native scenario submission. In other words, no infilled values^{28,29} have been considered because this would result in a narrowing of the percentile ranges for scenario uncertainties because for some species a large share of scenarios were infilled with central emission values. Scenarios that don't have a valid AR6 temperature assessment²⁸ are excluded from all calculations. Scenarios where reported F-gas totals in 2015 are outside the range 600–1800 Mt CO₂-equiv are excluded from F-gas calculations. Emissions are defined as in the IAMC reporting

template available from <https://data.ene.iiasa.ac.at/ar6-scenario-submission/#/about>.

Non-CO₂ emissions are harmonized in accordance with the AR6 scenario assessment protocol²⁸. This uses a multiplicative ratio to correct the SSP2-45 MESSAGE-GLOBIOM data to historical trends in 2014 where available in the AR6 database, then harmonises other scenarios to that trend in 2015 with a ratio that trends to 1 in 2080 (ref. ³⁰). Historical methane from AFOLU data is not available in the AR6 database, so this is estimated using the historical fraction of total methane from AFOLU found in the EDGAR database³¹ and used in the same way.

CO₂-warming equivalent CO₂-we emissions are calculated using the method described in ref. ²⁶. A GWP100 equivalence value of 29.9 is used for non-AFOLU methane and 27.2 for AFOLU methane based on ref. ³². Total CO₂-we emissions of methane are estimated by summing the two components.

Data availability

Emissions scenario data used in this study is available at ref. ¹⁵. Historical data is from ref. ³³ and ³⁴.

Code availability

Code required to estimate remaining carbon budgets is available at ref. ²⁷. Code to carry out the analysis in this study is available at ref. ³⁵ and <https://github.com/Rlamboll/NonCO2BudgetImplications>.

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Author contributions

J.R. initiated and designed the research, wrote the first draft, and led the review. R.D.L. wrote the analysis code, carried out the calculations, created the figures, and provided comments and feedback on the text.

Competing interests

The authors declare no competing interests.

Additional information


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