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# Substantial reductions in non-$CO_2$ 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-$CO_2$ emissions. Here, we uncover the non-$CO_2$ 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 ($CO_2$) 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 $CO_2$ emitted (known as the transient climate response to cumulative emissions of $CO_2$, or TCRE); an estimate of how global warming evolves once global $CO_2$ emissions are reduced to zero (known as the zero $CO_2$ emissions commitment[5], or ZEC); an adjustment for Earth system feedbacks that would otherwise not be captured; and finally, an estimate of how much non-$CO_2$ emissions will contribute to warming in the future compared to today. The latter requires assumptions both about future non-$CO_2$ emission levels and about their warming effect. Past studies have looked at the assumptions and impact of short-lived climate forcers[6], carbon-cycle and other uncertainties[7], climate policy choices[8] and energy system transformations[9] on the RCB[10]. Here, we uncover the broader non-$CO_2$ 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 ($CH_4$) and nitrous oxide ($N_2O$) 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 RCB[3], with more recent studies updating this quantification using identical methods and more recent data[11]. 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-$CO_2$ emissions to be explicitly estimated. They use internally consistent mitigation scenarios to extract relationships between peak warming and the additional warming caused by non-$CO_2$ emissions, including from non-$CO_2$ 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-$CO_2$ 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-$CO_2$ warming is then used to determine the remaining allowable warming for $CO_2$ (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 $CO_2$ only while being consistent with non-$CO_2$ 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-$CO_2$ 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 $GtCO_2$ depending on the strength of concurrent non-$CO_2$ reductions[3]. However, often lost in the communication of RCBs is the notion that all estimates assume stringent non-$CO_2$ mitigation, and that the 220 $GtCO_2$ variation represents the variation across different stringent non-$CO_2$ mitigation futures in line with the Paris Agreement. Another approach explored in the literature is to express all non-$CO_2$ emissions as $CO_2$-forcing-equivalent emissions and consider them as part of a total $CO_2$-forcing-equivalent budget[18]. The latter approach provides an alternative way forward, but does not allow us to easily understand the non-$CO_2$ contributions in terms of reductions of other main greenhouse gases such as methane. To clarify the non-$CO_2$ mitigation implied in RCB estimates, we here uncover the non-$CO_2$ reductions and estimate the consequences of a shortfall in non-$CO_2$ mitigation ambition.

## Results

Starting from the latest IPCC compilation of internally consistent mitigation scenarios[15] we estimate RCBs as in IPCC AR6[3,11] (see Supplementary Tables S1 and S2) and present the accompanying non-$CO_2$ assumptions. RCB estimates require deep reductions in non-$CO_2$ greenhouse gases (Table 1). RCB estimates in line with limiting warming to 1.5 °C assume 1.5 °C-compatible $CH_4$ 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-$CO_2$ emissions reductions in 2050 relative to 2020, and implied $CO_2$-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 | $N_2O$ | F-gases | $SO_2$ | BC | $CH_4$ | $CH_4$ AFOLU | $CH_4$ non-AFOLU | $N_2O$ | 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 |
| | 90% | −31 | −1 | −48 | 6 | −20 | −60 | −42 | −74 | 82 | −134 | 94 | 50 |
| 2.0 °C | 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 $CH_4$ emissions, $CH_4$ from agriculture, forestry and other land use (AFOLU), non-AFOLU $CH_4$ emissions, and global $N_2O$ emissions, and fluorinated gases (F-gases), as well for the aerosol and aerosol precursors $SO_2$ and black carbon (BC).

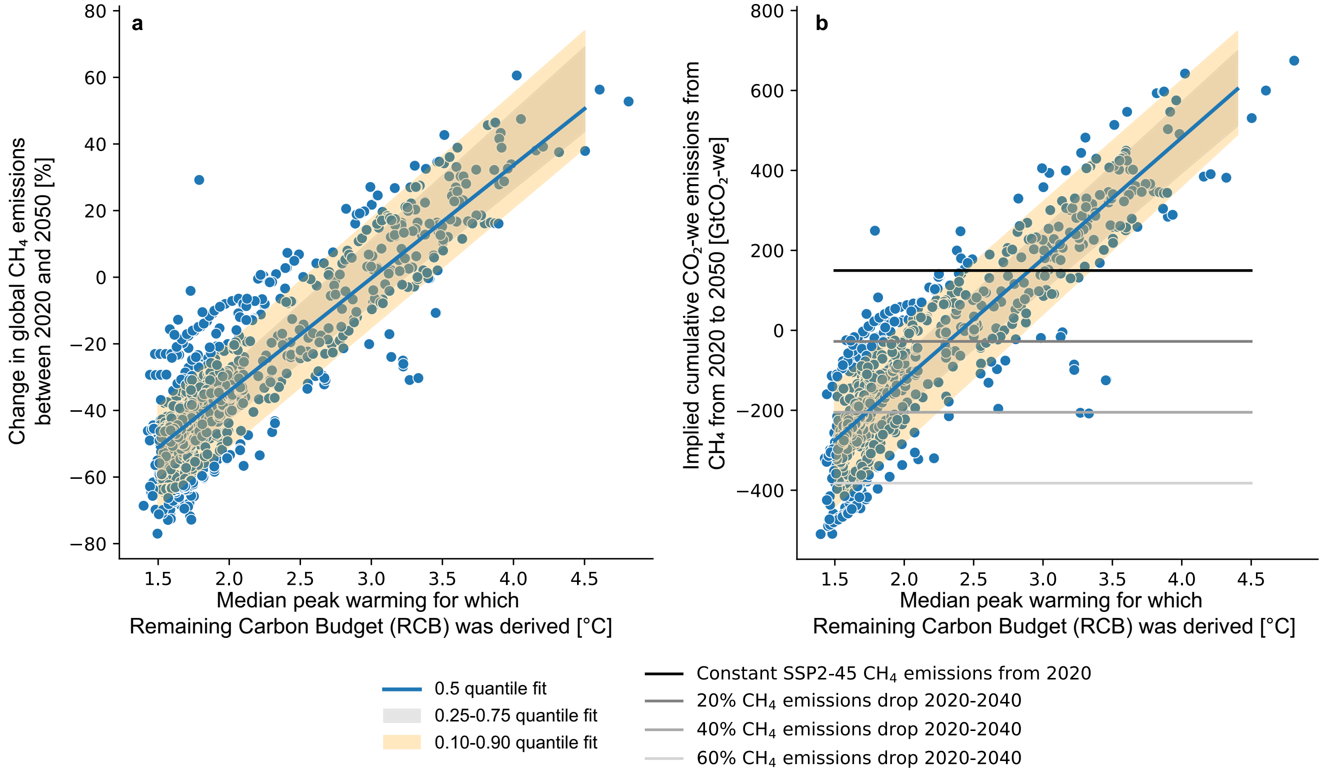


**Fig. 1 Global methane ($CH_4$) emissions reductions and their $CO_2$-warming-equivalent ($CO_2$-we) contributions compatible with remaining carbon budget estimates (RCBs) limiting warming to specific peak temperature levels. a** Change in global $CH_4$ emissions between 2020 and 2050 as a function of the peak warming limit for which an RCB is estimated; **b** $CO_2$-we emissions contribution of global $CH_4$ 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 database[15]. Horizontal lines in panel (**b**) show values for stylized global $CH_4$ emissions reductions between 2020 and 2050. Plots for other sectors or other non-$CO_2$ species are included in Supplementary Figs. S2–10.

warming to 1.7 °C and 2.0 °C, respectively. Global $N_2O$ 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 $CH_4$ and $N_2O$ reductions represent marked global emission reduction efforts. An illustration of the non-$CO_2$ 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-$CO_2$ greenhouse gas emissions globally[19]. Because of the distinct mitigation potential profile for agriculture[20], we also look at the specific non-$CO_2$ greenhouse assumptions for this sector. Global $N_2O$ emissions are dominated by the agricultural sector[19]. Emissions reductions mentioned above for total $N_2O$ emissions are therefore also applicable to agricultural $N_2O$ emissions. For methane, the reduction percentages over the 2020–2050 period differ across sectors, because the $CH_4$ mitigation potential in the agricultural is very different from the potential in the fossil-fuelled energy sector[21]. Agricultural $CH_4$ 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 $CH_4$ reductions from the fossil-fuel sector have to be deeper than the global total $CH_4$ emissions reductions. IPCC RCB estimates for 1.5 °C imply compatible fossil-fuel $CH_4$ 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 perfluorinated 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-$CO_2$ emissions that is often overlooked are aerosol (and their precursors) such as black carbon (BC) or $SO_2$ emissions, which are also air pollutants. These short-lived species are co-emitted with $CO_2$ through combustion processes, and are therefore projected to strongly decrease in low-emission scenarios[22]. Air pollution control policies can drive additional reductions[23]. This large degree of co-control of key air pollutants through $CO_2$ 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 $SO_2$ 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-$CO_2$ 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-$CO_2$ emissions. To this end, we estimate the $CO_2$-warming-equivalent ($CO_2$-we) emissions[26] implied by the median non-$CO_2$ greenhouse gas reductions assumed in RCB estimates. These $CO_2$-we emissions represent the internally consistent non-$CO_2$ changes that were included when estimating global RCBs. They also provide a direct way of quantifying the RCB impact of alternative assumptions.

Global $CO_2$-we contributions to RCBs between 2020 and 2050 for $CH_4$ are −275, −215, and −124 $GtCO_2$-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 $GtCO_2$-we (Fig. 1b). These central estimates allow the direct estimation of the RCB impact of alternative $CH_4$ evolutions over the next decade. Assuming global $CH_4$ emissions do not decline but instead are kept constant at 2020 levels would reduce the RCB by 431, 370, and 280 $GtCO_2$-we for RCBs compatible with 1.5 °C, 1.7 °C, and 2 °C, respectively. In other words, choosing not to reduce $CH_4$ 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 $GtCO_2$-we, highlighting the importance of deep reductions in $CH_4$. Similar adjustments can be estimated for alternative reductions of the split-up agricultural and non-agricultural $CH_4$ emissions and for $N_2O$ (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 $CO_2$-we emissions are to be considered as the internally consistent contributions from non-$CO_2$ emissions. Any deviations from this median assumption for non-$CO_2$ 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 $CH_4$ and $N_2O$ 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-$CO_2$ contributions are based on and estimated from the ensemble of mitigation scenarios compiled in the context of the IPCC Sixth Assessment Report[15]. 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 assessment[28] are excluded from all calculations. Scenarios where reported F-gas totals in 2015 are outside the range 600–1800 Mt $CO_2$-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-$CO_2$ emissions are harmonized in accordance with the AR6 scenario assessment protocol[28]. 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 database[31] and used in the same way.

$CO_2$-warming equivalent $CO_2$-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 $CO_2$-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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## References

1. IPCC. Annex VII: Glossary [Matthews, J. B. R., V. Möller, R. van Diemen, J. S., Fuglestvedt, V., Masson-Delmotte, C., Méndez, S. & Semenov, A. Reisinger (eds.)]. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* 2215–2256 https://doi.org/10.1017/9781009157896.022 (2021).
2. Rogelj, J., Forster, P. M., Kriegler, E., Smith, C. J. & Séférian, R. Estimating and tracking the remaining carbon budget for stringent climate targets. *Nature* **571**, 335–342 (2019).
3. Canadell, J. G. et al. Global Carbon and other Biogeochemical Cycles and Feedbacks. in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. Masson-Delmotte, V. et al.) (Cambridge University Press, 2021).
4. Matthews, D. H. et al. An integrated approach to quantifying uncertainties in the remaining carbon budget. *Commun. Earth Environ.* **2**, 1–11 (2021).
5. MacDougall, A. H. et al. Is there warming in the pipeline? A multi-model analysis of the zero emission commitment from CO2. *Biogeosci. Discuss.* **2020**, 1–45 (2020).
6. Rogelj, J., Meinshausen, M., Schaeffer, M., Knutti, R. & Riahi, K. Impact of short-lived non-CO2 mitigation on carbon budgets for stabilizing global warming. *Environ. Res. Lett.* **10**, 075001 (2015).
7. Mengis, N., Partanen, A.-I., Jalbert, J. & Matthews, H. D. 1.5 °C carbon budget dependent on carbon cycle uncertainty and future non-$CO_2$ forcing. *Sci. Rep.* **8**, 5831 (2018).
8. Rogelj, J. et al. Mitigation choices impact carbon budget size compatible with low temperature goals. *Environ. Res. Lett.* **10**, 075003 (2015).
9. van Vuuren, D. P. et al. Carbon budgets and energy transition pathways. *Environ. Res. Lett.* **11**, 075002 (2016).
10. Matthews, H. D. et al. Opportunities and challenges in using remaining carbon budgets to guide climate policy. *Nat. Geosci.* **13**, 769–779 (2020).
11. Forster, P. M. et al. Indicators of Global Climate Change 2022: annual update of large-scale indicators of the state of the climate system and human influence. *Earth Syst. Sci. Data* **15**, 2295–2327 (2023).
12. Rogelj, J. et al. Mitigation pathways compatible with 1.5 °C in the context of sustainable development. in *Global Warming of 1.5 °C: an IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and*

*related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* (eds. Flato, G. et al.) 93–174 (IPCC/WMO, 2018).
13. Huppmann, D., Rogelj, J., Kriegler, E., Krey, V. & Riahi, K. A new scenario resource for integrated 1.5 °C research. *Nat. Clim. Change* **8**, 1027–1030 (2018).
14. Huppmann, D. et al. *IAMC 1.5 °C Scenario Explorer and Data hosted by IIASA*. (Integrated Assessment Modeling Consortium & International Institute for Applied Systems Analysis, 2018). https://doi.org/10.22022/SR15/08-2018.15429.
15. Byers, E. et al. AR6 Scenarios Database. https://doi.org/10.5281/zenodo.5886912 (2022).
16. Nicholls, Z. et al. Cross-Chapter Box 7.1: Physical emulation of Earth System Models for scenario classification and knowledge integration in AR6. in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. Masson-Delmotte, V. et al.) (Cambridge University Press, 2021).
17. Guivarch, C. et al. IPCC, 2022: Annex III: Scenarios and modelling methods. in *IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, 2022).
18. Jenkins, S. et al. Quantifying non-CO2 contributions to remaining carbon budgets. *npj Clim. Atmos. Sci.* **4**, 1–10 (2021).
19. Dhakal, S. et al. Emissions Trends and Drivers. in *IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. Shukla, P. R. et al.) (Cambridge University Press, 2022). https://doi.org/10.1017/9781009157926.004.
20. Nabuurs, G.-J. et al. Agriculture, Forestry and Other Land Uses (AFOLU). in *IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, 2022).
21. Harmsen, M. et al. The role of methane in future climate strategies: mitigation potentials and climate impacts. *Clim. Change* **163**, 1409–1425 (2020).
22. Rogelj, J. et al. Air-pollution emission ranges consistent with the representative concentration pathways. *Nat. Clim. Change* **4**, 446–450 (2014).
23. Rao, S. et al. Future air pollution in the Shared Socio-economic Pathways. *Global Environ. Change* **42**, 346–358 (2017).
24. IPCC. Summary for Policymakers. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* 3−32 https://doi.org/10.1017/9781009157896.001 (2021).
25. Szopa, S. et al. Short-Lived Climate Forcers. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* 817–922 https://doi.org/10.1017/9781009157896.008 (2021).
26. Smith, M. A., Cain, M. & Allen, M. R. Further improvement of warming-equivalent emissions calculation. *npj Clim. Atmos. Sci.* **4**, 1–3 (2021).
27. Lamboll, R. D. & Rogelj, J. Code for estimation of remaining carbon budget in IPCC AR6 WGI. https://doi.org/10.5281/zenodo.6373365 (2022).
28. Kikstra, J. S. et al. The IPCC Sixth Assessment Report WGIII climate assessment of mitigation pathways: from emissions to global temperatures. *Geosci. Model Dev.* **15**, 9075–9109 (2022).
29. Lamboll, R. D., Nicholls, Z. R. J., Kikstra, J. S., Meinshausen, M. & Rogelj, J. Silicone v1.0.0: an open-source Python package for inferring missing emissions data for climate change research. *Geosci. Model Dev.* **13**, 5259–5275 (2020).
30. Gidden, M. J. et al. A methodology and implementation of automated emissions harmonization for use in Integrated Assessment Models. *Environ. Model. Softw.* **105**, 187–200 (2018).
31. Joint Research Centre (European Commission) et al. *$CO_2$ emissions of all world countries: JRC/IEA/PBL 2022 report* (Publications Office of the European Union, 2022).
32. Forster, P. et al. The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. Masson-Delmotte, V. et al.) (Cambridge University Press, 2021).
33. Gütschow, J., Jeffery, L. & Gieseke, R. *The PRIMAP-hist national historical emissions time series (1850-2016). V. 2.0.* (GFZ Data Services, 2019). https://doi.org/10.5880/PIK.2019.001.
34. JRC/PBL. *Emission Database for Global Atmospheric Research (EDGAR), release version 4.3.1.* (Joint Research Centre of the European Commission/PBL Netherlands Environmental Assessment Agency, 2016).
35. Rogelj, J. & Lamboll, R. Non-CO2 emissions reductions implied by IPCC estimates of the Remaining Carbon Budget. https://www.researchsquare.com 10.21203/rs.3.rs-3326772/v1 (2023).

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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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