nature climate change

Article

https://doi.org/10.1038/s41558-022-01508-0

Ratcheting of climate pledges needed to limit peak global warming

Received: 3 May 2022

Accepted: 21 September 2022

Published online: 10 November 2022

Check for updates

Gokul Iyer [1,4], Yang Ou [1,4], James Edmonds [1], Allen A. Fawcett [2], Nathan Hultman [3], James McFarland[2], Jay Fuhrman[1], Stephanie Waldhoff [1] & Haewon McJeon [1]

The new and updated emission reduction pledges submitted by countries ahead of the Twenty-Sixth Conference of Parties represent a meaningful strengthening of global ambition compared to the 2015 Paris pledges. Yet, limiting global warming below 1.5 °C this century will require countries to ratchet ambition for 2030 and beyond. Here, we explore a suite of emissions pathways to show that ratcheting near-term ambition through 2030 will be crucial to limiting peak temperature changes. Delaying ratcheting ambition to beyond 2030 could still deliver end-of-century temperature change of less than 1.5 °C but would result in higher temperature overshoot over many decades with the potential for adverse consequences. Ratcheting near-term ambition would also deliver benefits from enhanced non-CO_2 mitigation and facilitate faster transitions to net-zero emissions systems in major economies.

Many countries and other non-national actors announced new climate ambition, actions and targets ahead of the Twenty-Sixth Conference of Parties (COP26), held in Glasgow in November 2021. COP26 provided the first real demonstration of the 2015 Paris Agreement's mechanism to regularly revisit and enhance national climate strategies[1]. By the end of COP26, 151 countries submitted updated and new nationally determined contributions (NDCs) outlining plans to cut GHG emissions by 2030[2]. Many countries also communicated official or unofficial long-term strategies (LTSs) that outline emission reduction strategies through the mid-century[3] and net-zero emissions targets[4]. Although the updated and new 2030 pledges suggest higher ambition compared to the 2015 Paris pledges[5,6], limiting global warming below 1.5 °C this century—the aspirational goal of the Paris Agreement—will require countries to further ratchet or increase ambition in 2030 and beyond[6–12]. Importantly, recognizing the need for countries to ratchet their ambition beyond their current pledges, Article IV of the Glasgow Climate Pact accelerates the previously expected timeline for revising these NDCs and calls for countries "to revisit and strengthen the 2030 targets in their nationally determined contributions ... to align with the Paris Agreement temperature goal by the end of 2022"[13]. In addition, the Pact calls for countries that have "not yet done so to communicate new or updated nationally determined contributions and long-term low greenhouse gas emission development strategies to net-zero emissions by or around mid-century". The Pact also "emphasizes the urgent need for Parties to increase their efforts to collectively reduce emissions through accelerated action".

As the international community responds to these calls for ratcheting ambition, there is a strong need to understand both the long-term temperature outcomes of ratcheting ambition in 2030 and beyond and what this ratcheting implies for sectoral and regional emissions. To address this need, we explore a suite of high ambition emissions pathways—developed using the Global Change Analysis Model (GCAM; Methods)[14]—in which countries are assumed to use various combinations of three strategies to ratchet ambition: (1) increasing near-term actions through 2030, (2) accelerating post-2030 emissions reductions and (3) moving forward the timing of dates that countries pledge to hit net-zero emissions. We then use a reduced-form climate model (Hector)[15] to compute the end-of-century and peak temperature change implications of the emissions pathways. Our study builds off and extends previous modelling studies that have explored high ambition emissions pathways[6,8,16–20]. In doing so, our study makes a timely contribution by exploring pathways that take the 2021 pledges made until

[1]Joint Global Change Research Institute, Pacific Northwest National Laboratory and University of Maryland, College Park, MD, USA. [2]US Environmental Protection Agency, Washington, DC, USA. [3]Center for Global Sustainability, School of Public Policy, University of Maryland, College Park, MD, USA. [4]These authors contributed equally: Gokul Iyer, Yang Ou. e-mail: haewon.mcjeon@pnnl.gov

https://doi.org/10.1038/s41558-022-01508-0

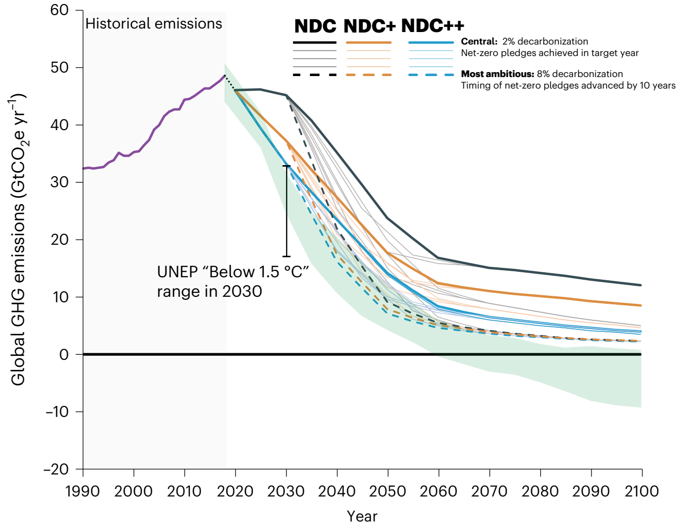

Fig. 1 | Global GHG emissions in the pathways modelled using the GCAM. The emissions pathways vary across assumptions about ambition level in 2030, post-2030 minimum decarbonization rate and timing of net-zero for countries with net-zero pledges. See text for detailed description of assumptions. The black colour corresponds to the 'NDC' cases, orange to the 'NDC+' cases and blue to the 'NDC++' cases. Each colour group comprises nine pathways. The thick bold lines in each colour group correspond to the central assumptions about post-2030 minimum decarbonization (2%) and year of net-zero (target year as specified). The thick dashed lines correspond to the most ambitious pathway within each colour group. The lighter lines within each colour group correspond to different assumptions about the post-2030 minimum decarbonization rate and timing of net-zero pledges. The shaded green area represents 15–85 percentile range of 1.5 °C pathways with no or limited overshoot from the IPCC SR1.5 report[18]. See Supplementary Section 2 and Supplementary Table 1 for a mapping of our pathways with the recently published IPCC Sixth Assessment Report[20,52].

the end of COP26 as a starting point and providing important insights on the long-term temperature change and sectoral and regional emissions implications of ratcheting ambition beyond those pledges (see Supplementary Section 1 for a detailed literature review).

Emissions pathways

Our emissions pathways (Fig. 1) explore a combination of three strategies that countries might use to ratchet and achieve ambition: (1) increasing ambition in the near-term through 2030, (2) increasing post-2030 decarbonization rates or (3) achieving net-zero pledges sooner.

In 2030, countries are assumed to achieve one of three ambition levels, namely, NDC, NDC+ and NDC++. Our central assumption is that countries achieve the updated or new pledges submitted until the end of COP26 (Methods). To construct the NDC+ and NDC++ sensitivities, we begin with the ambition level implied in the updated or new pledges as assessed by Climate Action Tracker (CAT)[21,22]. CAT provides one of five rating categories for the country pledges ('1.5 °C Paris Agreement compatible', 'almost sufficient', 'insufficient', 'highly insufficient' and 'critically insufficient'). In the NDC+ sensitivity, we assume that countries rated 'critically insufficient' and 'highly insufficient' by CAT reduce their emissions by 30% below their current NDC. In the NDC++ sensitivity, we assume that countries rated 'critically insufficient', 'highly insufficient', 'insufficient' and 'not assessed' by CAT also reduce their emissions by 30% below their current NDC. Although arbitrary, the 30% assumption enables us to explore the implications of greater ambition and also helps ensure that global 2030 emissions are consistent with existing high ambition scenarios. The GHG emissions in 2030 in our NDC++ pathways lie at the higher end of pathways explored in the recent modelling literature[6,23]. In an additional sensitivity analysis section included in the Supplementary Information, we explore more ambitious emission cuts in 2030 that lie within the literature range (Supplementary Fig. 1). We also examine the sensitivity of our results to the methodology used to develop the NDC+ and NDC++ assumptions (Supplementary Section 2).

Beyond 2030, countries are assumed to achieve the same level of decarbonization rate—defined as the annual rate of improvement in GHG emissions per unit of gross domestic product (GDP)—as the rate between 2015 and 2030 or a minimum rate if their decarbonization rate is below this minimum rate. Our central assumption about the post-2030 minimum decarbonization rate is 2% and our sensitivity assumptions are 5% and 8%. These assumptions are consistent with previous studies and are consistent with the average and high rates observed historically (Methods).

In all our pathways, countries are assumed to achieve their official LTSs and net-zero pledges if any. Countries with LTSs are assumed to achieve their LTSs in the target year following a linear path (Methods). Beyond the target year, countries are assumed to follow a path defined by the minimum decarbonization rate. Our pathways vary in their assumptions about the timing of net-zero pledges if any. Our central assumption is that countries with net-zero pledges achieve net-zero emissions in the target year following a linear path and then continue to keep their emissions constant beyond that year. We consider two alternative sensitivity assumptions in which countries with net-zero pledges advance the timing of achieving net-zero emissions by 5 or 10 years.

The full combination of the above assumptions results in 27 emissions pathways. We note that our high ambition pathways are meant to be illustrative and they do not imply feasibility, which would require accounting for a variety of considerations including ethical and political[24–26].

Temperature outcomes

Using a simple reduced-form climate model (Hector; Methods)[15] we study the implications of the emissions pathways for end-of-century and peak global mean surface temperature changes (Fig. 2). Our results show—consistent with other studies—that if countries achieve their 2021 NDCs, official LTSs and net-zero pledges as stated, global surface temperature change can be limited to <2 °C warming this century[5,6,9–12]. In addition, many of our high ambition pathways with the NDC+ and NDC++ emission levels in 2030 result in <1.5 °C temperature change in 2100. Even if ratcheting of ambition is delayed to beyond 2030, end-of-century temperature change can be returned to <1.5 °C. However, that would require substantial ratcheting of post-2030 ambition beyond historically observed decarbonization rates (Methods)—as in the pathways in which countries achieve the NDC emission level in 2030 followed by an 8% minimum decarbonization rate.

Ratcheting ambition in the near-term—as in our NDC++ pathways—has marked implications for peak temperature changes. Ratcheting ambition in the near-term results in lower levels of peak warming. For instance, the peak temperature change in the pathway with NDC emission level in 2030 followed by a 8% minimum decarbonization rate and net-zero pledges in the specified target years is 1.77 °C compared to 1.82 °C in the pathway with NDC emission level in 2030 followed by a 2% minimum decarbonization rate. By contrast, the peak temperature change in the pathway with NDC++ emissions in 2030 followed by a 2% minimum decarbonization rate and net-zero pledges in the specified target years is 1.68 °C. Ratcheting ambition in the near- and long-term—as in the pathways with NDC++ emission level in 2030 followed by an 8% minimum decarbonization rate—reduces peak temperature change further (peak temperature changes of 1.67 °C if net-zero pledges are assumed to be achieved in the specified target years). This is an important finding since higher peak temperature changes and therefore higher temperature overshoots—that is, an exceedance of global mean temperature change above the intended threshold before returning to

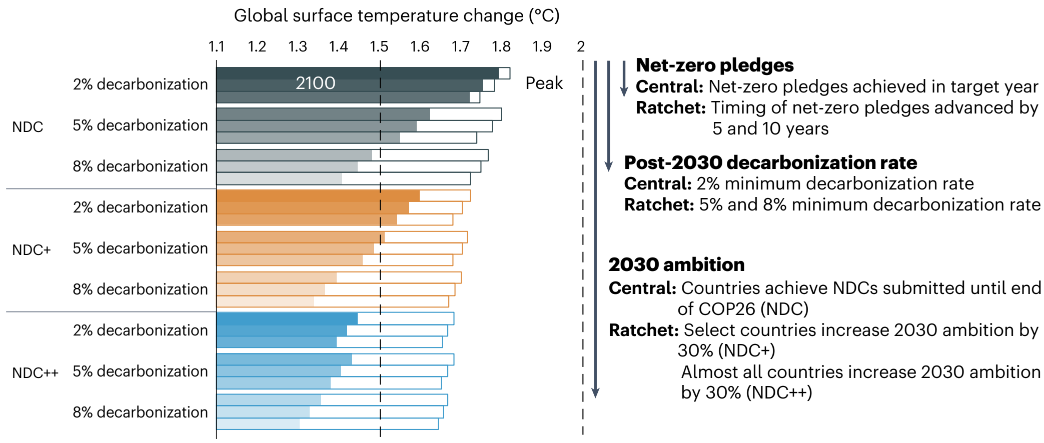

Fig. 2 | Temperature change in 2100 (inner bars) and peak temperature change (outer bars) outcomes of the emissions pathways explored in this study. The grey colour corresponds to the 'NDC' cases, orange to the 'NDC+' cases and blue to the 'NDC++' cases. See text for description about the construction of the NDC+ and NDC++ cases. The lighter shades within each colour group correspond to different assumptions about the post-2030 minimum decarbonization rate. While the first bar within each colour and shading group corresponds to the central case in which countries with net-zero pledges are assumed to achieve their pledges in the target year as stated, the second and third bars assume that countries advance the accomplishment of their pledges by 5 and 10 years respectively.

below the intended level—could expose natural and human systems to substantial risks potentially leading to irreversible and adverse consequences such as the loss of some ecosystems[27–29].

Furthermore, ratcheting near-term ambition could markedly reduce the number of years of overshoot before returning to 1.5 °C this century (Supplementary Table 1 and Supplementary Fig. 2). For example, the pathways with NDC emission level in 2030 followed by a 2% or 5% minimum decarbonization rate and net-zero pledges in the specified target years do not return to 1.5 °C this century and the number of years of overshoot in the pathway with an 8% minimum decarbonization rate is 67. By contrast, in the pathways with NDC++ emission level in 2030, the number of years of overshoot reduces to 58, 56 and 47 years respectively.

Advancing the timing of net-zero pledges can be an important ratcheting strategy as it could provide the extra push required in the long-term to return 2100 warming to <1.5 °C and further reduce temperature overshooting. For example, in the pathway with NDC+ emissions in 2030 followed by a 5% minimum decarbonization rate and net-zero pledges in the specified target years, the 2100 and peak temperature changes are, respectively, 1.51 °C and 1.72 °C. Advancing the timing of net-zero pledges by 10 years brings the 2100 and peak temperature changes down to 1.46 °C and 1.68 °C.

Sectoral implications of ratcheting ambition

Ratcheting ambition would entail rapid reductions in CO_2 emissions from all sectors of the energy system (Fig. 3 and Supplementary Fig. 4), especially through the mid-century. While some sectors (for example, electricity, buildings and industry) decarbonize faster due to the availability of many low-carbon technology alternatives, others (for example, transportation) decarbonize slower due to fewer options.

Ratcheting ambition in the near-term results in quicker transitions to net-zero emissions energy systems[30–32]. For example, in the pathway with NDC emissions in 2030 followed by a 2% minimum decarbonization rate, global CO_2 emissions do not get to net-zero this century. Ratcheting near-term ambition—as in the pathway with NDC++ emissions in 2030 followed by 2% minimum decarbonization rate—advances the year of global net-zero CO_2 emissions to 2053. Ratcheting both near-term and long-term ambition—as in the pathway with NDC++ emissions in 2030 followed by an 8% minimum decarbonization rate—advances the year of global net-zero CO_2 emissions further to 2052 (Supplementary Table 1). Such accelerated declines in CO_2 emissions are accompanied by rapid transformations throughout the global energy system to phase out fossil fuel-based infrastructures and scale up low-carbon technologies such as renewables, nuclear and carbon capture and storage (Supplementary Figs. 5–8).

Ratcheting near-term ambition also implies greater reductions in non-CO_2 emissions, some of which have higher global warming potentials and shorter atmospheric lifetimes and therefore play an important role in both stabilizing long-term temperature change and limiting peak near-term warming (Fig. 3). Non-CO_2s respond to climate policy in two ways[33]. First, fuel switching and associated phasing out of carbon-intensive fuels due to climate policy reduce associated non-CO_2 emissions (for example, fugitive methane emissions from resource production). Thus, higher CO_2 ambition implies higher non-CO_2 ambition. Second, non-CO_2 emissions that are largely unaffected by fuel switching such as hydrofluorocarbon (HFC) emissions from cooling energy use and industrial process emissions (perfluorocarbons (PFCs) and sulfur hexafluoride) respond to climate policy through the implementation of additional control measures. In our analysis, the NDC+ and NDC++ pathways result, respectively, in 18% and 24% reduction in methane emissions from the energy system in 2030 relative to 2020. In terms of total methane emissions from energy and agricultural systems, the reduction is, respectively, 4% and 8%. In comparison, over a hundred countries made a commitment under the Global Methane Pledge—a key outcome of COP26—to collectively reduce methane emissions by at least 30% (ref. [34]). Future work could explore higher ambition to reduce methane emissions—especially from agriculture—than suggested by our scenarios.

Nevertheless, some non-CO_2 emissions such as methane emissions from cattle due to enteric fermentation are hard to abate[35–37]. Hence, achieving net-zero GHG emissions beyond 2030 and continued decarbonization over the longer term will require the deployment of carbon dioxide removal (CDR) technologies[38,39] to offset these emissions. Our pathways assume the availability of CDR technologies such as bioenergy in combination with carbon capture and storage (BECCS) and direct air capture (DAC) in addition to terrestrial sinks[40] and assume that the relative roles of CDR deployment versus mitigation in other sectors largely depend on economics. Although the scale of CDR in our pathways is consistent with the extant literature (Supplementary Figs. 9 and 10), an important caveat that could affect the feasibility and scale of

https://doi.org/10.1038/s41558-022-01508-0

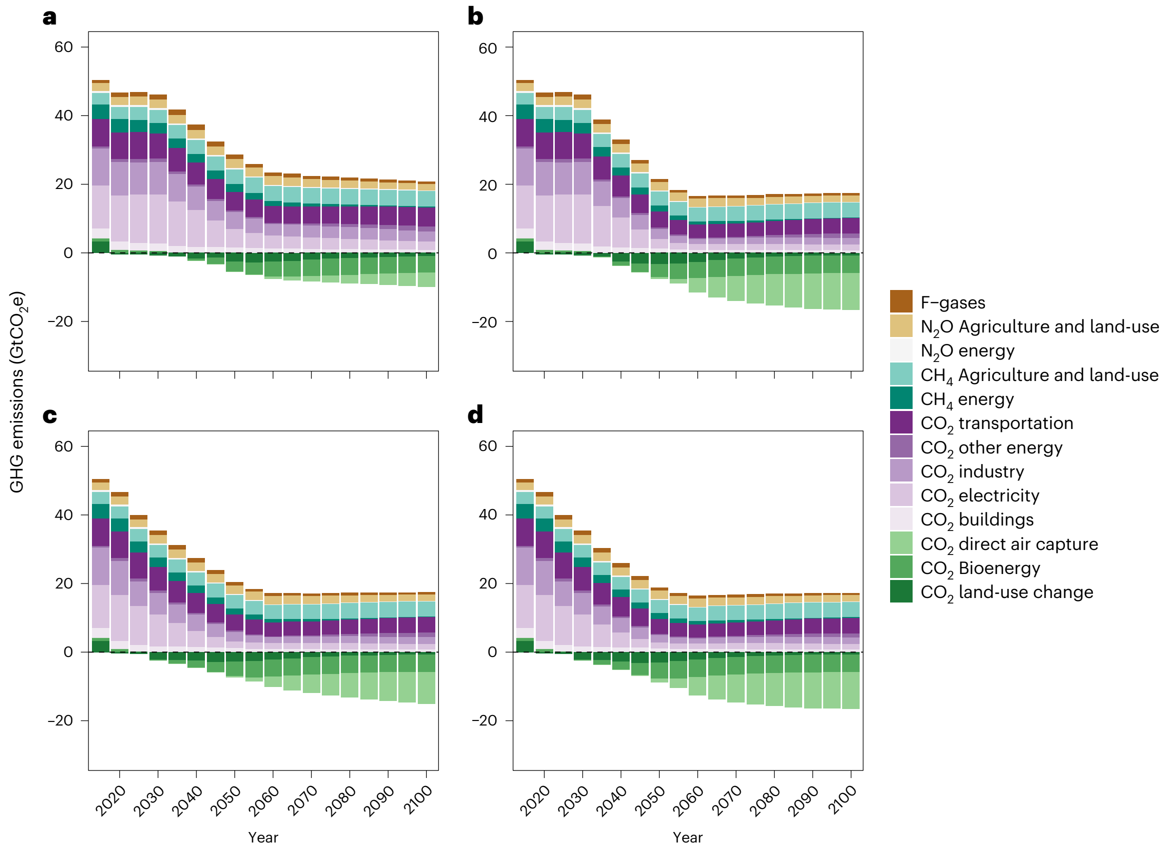

Fig. 3 | GHG emissions by sector and species in a subset of the pathways explored in the study. a, NDC/2% decarbonization rate/net-zero pledges in target years. **b**, NDC/8% decarbonization rate/net-zero pledges in target years. **c**, NDC++/2%decarbonization rate/net-zero pledges in target years. **d**, NDC++/8% decarbonization rate/net-zero pledges in target years. See Supplementary Fig. 3 for GHG emissions by sector and species in all of the pathways explored in this study and Supplementary Fig. 4 for a version of the figure with differences in panels **b**, **c** and **d** relative to **a**.

CDR deployment that is not fully accounted for in our pathways is that they could interact with societal priorities other than climate, creating varying degrees of synergies and tradeoffs depending on the type and scale of CDR measures used[41–44]. In addition, since not all countries are equally endowed with CDR potential, achieving net-zero pledges and ratcheting ambition might need to be supported by cooperative strategies and/or trade[38,45]. A simple sensitivity analysis that explores the implications of limited CDR availability suggests that the high ambition pathways explored in this study are feasible under no availability of DAC but that results in greater reductions in CO_2 emissions from energy and industrial sectors (Supplementary Figs. 11 and 12). Further research is required to better understand the role of CDR and emissions trading in high ambition emissions pathways[16].

Regional implications of ratcheting ambition

The implications of ratcheting ambition for regional emissions depend on whether countries currently have net-zero pledges. For countries with net-zero pledges (for example, China, India and the USA), cumulative emissions grow and then remain flat beyond the year of net-zero under the pathway with central assumptions (Fig. 4). For such countries, ratcheting ambition in the near-term—as in the NDC++ pathways—results in slower growth of emissions and a plateauing of emissions at a lower peak level. In addition, ratcheting ambition in the near-term for such countries also facilitates an advancement of the timing of net-zero CO_2 emissions (Fig. 5). For example, ratcheting near-term ambition from NDC to NDC++ emissions in 2030 in China, Brazil and the USA results in an advancement of the year of net-zero CO_2 emissions from 2058, 2041 and 2046 to 2057, 2037 and 2044, respectively. This advancement occurs despite the target years for the official net-zero pledges—which are modelled in terms of net-zero GHG emissions for the above countries—remaining unchanged (see Methods and Supplementary Table 2 for details on how net-zero pledges are modelled) because it facilitates a more rapid phase out of fossil-fuel-based infrastructure. Advancing the target year for net-zero pledges further advances the timing of net-zero CO_2 emissions (Supplementary Table 3).

By contrast, cumulative emissions for emerging economies without net-zero pledges (for example, Middle East, Africa and Southeast Asia) grow throughout the century under the NDC pathways—albeit at a slower rate under the 8% minimum decarbonization rate assumption (Fig. 4). For such countries, ratcheting ambition both in the near-term and in the long-term—as in the pathway with NDC++ emissions in 2030 followed by an 8% minimum decarbonization rate—is critical to accelerate the phase out of fossil-based infrastructure and consequently get to net-zero CO_2 emissions sooner (Fig. 5).

Discussion

This study provides an ex-ante scientific underpinning to help design revised and more ambitious pledges in response to the calls made in the 2021 Glasgow Climate Pact and to understand their potential temperature implications during the century. Our results underscore the importance that countries ratchet their ambition in the near-term—through 2030—to reduce overshooting and thus maximize long-term climate benefits. Our study also underscores the potential hazards of delaying the timing of ratcheting ambition. Although limiting global warming to <1.5 °C by the end of the century is possible even if ratcheting ambition

https://doi.org/10.1038/s41558-022-01508-0

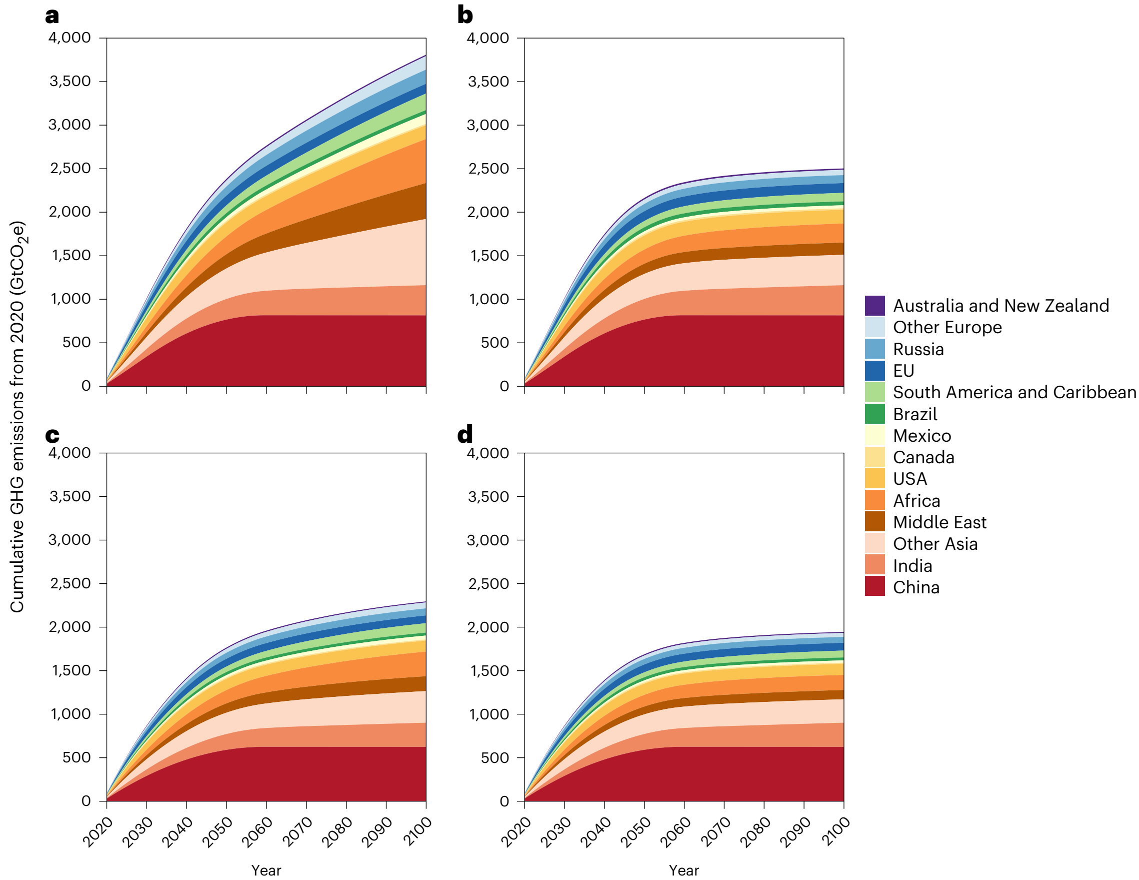

Fig. 4 | Cumulative GHG emissions by region in a subset of the pathways explored in the study. **a**, NDC/2% decarbonization rate/net-zero pledges in target years. **b**, NDC/8% decarbonization rate/net-zero pledges in target years. **c**, NDC++/2%decarbonization rate/net-zero pledges in target years. **d**, NDC++/8% decarbonization rate/net-zero pledges in target years. See Supplementary Fig. 13 for GHG emissions by region in all of the pathways explored in this study.

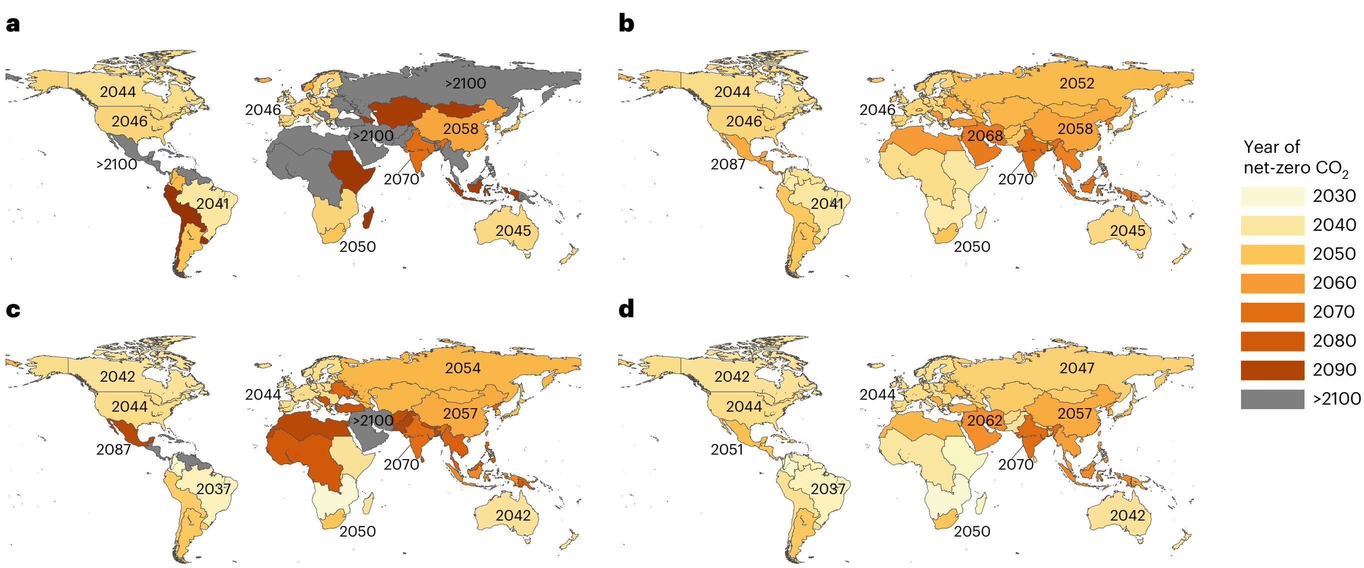

Fig. 5 | Year of net-zero CO_2 emissions in a subset of the pathways explored in the study. **a**, NDC/2% decarbonization rate/net-zero pledges in target years. **b**, NDC/8% decarbonization rate/net-zero pledges in target years. **c**, NDC++/2%decarbonization rate/net-zero pledges in target years. **d**, NDC++/8% decarbonization rate/net-zero pledges in target years. See Supplementary Table 3 for year of net-zero CO_2 emissions in all of the pathways explored in this study. Global maps in this figure are created using an open-source R package[53] and documented in ref. [54]. ">2100" indicates the year of net-zero CO_2 emission occurs after 2100.

is delayed, it would result in higher overshooting during the century potentially for a period spanning decades which could lead to irreversible and adverse consequences for human and natural systems. Delaying ratcheting of ambition may also require accelerating post-2030 decarbonization to rates that are substantially higher than historical rates. For analysts, these results emphasize the need for future research to explore emissions pathways that focus not only end-of-century temperature targets but also alternative pathways that limit the degree of temperature overshoot during the century—especially those with higher near-term ambition than implied by the current set of NDCs. A few studies have begun to explore such alternative pathways[23,29] but more community-wide studies—including intermodel comparison efforts—could help collect robust insights about the costs and benefits of ratcheting ambition in the near-term and the technological options that could facilitate the implementation of higher near-term ambition.

Our study suggests a strong potential for non-CO_2 mitigation in facilitating the higher ambition needed. Previous analyses have shown that to limit temperature change to 1.5 °C, mitigation strategies focused only on CO_2 reduction could require getting to net-zero two decades sooner than comprehensive strategies that include non-CO_2s as well[33]. While the Global Methane Pledge[34] is a step in the right direction to motivate higher non-CO_2 ambition, comprehensive strategies that account for a wider suite of GHGs would ultimately be required to enable cost-effective emission reductions[33,46].

Our results also suggest that ratcheting near-term ambition could enable faster transitions required to accomplish net-zero pledges, especially in major emitting economies. These transitions could very well be accomplished with limited availability of nascent technologies such as CDR. However, the economic implications of these transitions would hinge on the availability of CDR and other nascent technologies such as CCS and the ability of grid infrastructures to expand rapidly as technologies such as renewables scale up. The speed and scale at which these technologies can be deployed depend on a variety of factors, such as costs, access to financial capital, supply-chain issues, land-use and geophysical constraints and other institutional, social and behavioural factors[26,47–50]. Such factors could imply severe economic consequences[47,48]. Future work should consider these factors and other real-world political and ethical ramifications of ratcheting ambition to better understand the feasibility of the high ambition pathways explored in this study[51]. Nonetheless, ratcheting near-term ambition and concurrently testing out and establishing policies and institutional infrastructures that phase out fossil fuels and incentivize research and development and deployment of more nascent technologies in the near-term will be crucial to facilitate deeper emissions reductions in the long-term needed to cost-effectively accomplish the long-term goals of the Paris Agreement[39].

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-022-01508-0.

References

1. *The Paris Agreement* (UNFCCC, 2021); https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement
2. *Nationally Determined Contributions (NDCs)* (UNFCCC, 2021); https://unfccc.int/process-and-meetings/the-paris-agreement/nationally-determined-contributions-ndcs/nationally-determined-contributions-ndcs#eq-1
3. *Communication of Long-term Strategies* (UNFCCC, 2021); https://unfccc.int/process/the-paris-agreement/long-term-strategies
4. *CAT Net Zero Target Evaluations* (Climate Action Tracker, 2021); https://climateactiontracker.org/global/cat-net-zero-target-evaluations/
5. Ou, Y. et al. Can updated climate pledges limit warming well below 2°C?. *Science* **374**, 693–695 (2021).
6. *Emissions Gap Report 2021: The Heat Is On—A World of Climate Promises Not Yet Delivered* (United Nations Environment Programme, 2021).
7. *Glasgow's 2030 Credibility Gap: Net Zero's Lip Service to Climate Action* (Climate Action Tracker, 2021).
8. Grant, N. The Paris Agreement's ratcheting mechanism needs strengthening 4-fold to keep 1.5 °C alive. *Joule* https://doi.org/10.1016/j.joule.2022.02.017 (2022).
9. Meinshausen, M. et al. Realization of Paris Agreement pledges may limit warming just below 2 °C. *Nature* **604**, 304–309 (2022).
10. IPCC. Summary for Policymakers. In *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 Univ. Press, 2022).
11. Lecocq, F. et al. in *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.) Ch. 4, (Cambridge Univ. Press, 2022).
12. den Elzen, M. G. J. et al. Updated nationally determined contributions collectively raise ambition levels but need strengthening further to keep Paris goals within reach. *Mitig. Adapt. Strateg. Glob. Change* **27**, 33 (2022).
13. *The Glasgow Climate Pact* (UNFCCC, 2021); https://unfccc.int/sites/default/files/resource/cop26_auv_2f_cover_decision.pdf
14. Calvin, K. et al. GCAM v5.1: representing the linkages between energy, water, land, climate, and economic systems. *Geosci. Model Dev.* **12**, 677–698 (2019).
15. Hartin, C. A., Patel, P., Schwarber, A., Link, R. P. & Bond-Lamberty, B. P. A simple object-oriented and open-source model for scientific and policy analyses of the global climate system—Hector v1.0. *Geosci. Model Dev.* **8**, 939–955 (2015).
16. Holz, C., Siegel, L. S., Johnston, E., Jones, A. P. & Sterman, J. Ratcheting ambition to limit warming to 1.5 °C–trade-offs between emission reductions and carbon dioxide removal. *Environ. Res. Lett.* **13**, 064028 (2018).
17. Bharadwaj, B. & Brierley, C. *Ratcheting up Ambition in Climate Policy* (Environmental Change Research Centre, 2017); https://discovery.ucl.ac.uk/id/eprint/1541174/1/ecrc_report_182_Bharadwaj_Brierley.pdf
18. IPCC *Special Report on Global Warming of 1.5 °C* (eds Masson-Delmotte, V. et al.) (WMO, 2018).
19. Iyer, G. C. et al. The contribution of Paris to limit global warming to 2 °C. *Environ. Res. Lett.* **10**, 125002 (2015).
20. Riahi, K. et al. in *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.) Ch. 3, (Cambridge Univ. Press, 2022).
21. *Countries* (Climate Action Tracker, 2021); https://climateactiontracker.org/countries/
22. *Rating System* (Climate Action Tracker, 2021); https://climateactiontracker.org/countries/rating-system/
23. Riahi, K. et al. Cost and attainability of meeting stringent climate targets without overshoot. *Nat. Clim. Change* **11**, 1063–1069 (2021).
24. van den Berg, N. J. et al. Implications of various effort-sharing approaches for national carbon budgets and emission pathways. *Clim. Change* **162**, 1805–1822 (2019).
25. Rajamani, L. et al. National 'fair shares' in reducing greenhouse gas emissions within the principled framework of international environmental law. *Clim. Policy* **21**, 983–1004 (2021).
26. Peng, W. et al. Climate policy models need to get real about people—here's how. *Nature* **594**, 174–176 (2021).
27. Hoegh-Guldberg, O. et al. 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 Masson-Delmotte, V. et al.) Ch. 3, (Cambridge Univ. Press, 2018).

28. Geden, O. & Löschel, A. Define limits for temperature overshoot targets. *Nat. Geosci.* **10**, 881–882 (2017).
29. Drouet, L. et al. Net zero-emission pathways reduce the physical and economic risks of climate change. *Nat. Clim. Change* **11**, 1070–1076 (2021).
30. Davis, S. J. et al. Net-zero emissions energy systems. *Science* https://doi.org/10.1126/science.aas9793 (2018).
31. Azevedo, I., Bataille, C., Bistline, J., Clarke, L. & Davis, S. Net-zero emissions energy systems: what we know and do not know. *Energy Clim. Change* https://doi.org/10.1016/j.egycc.2021.100049 (2021).
32. DeAngelo, J. et al. Energy systems in scenarios at net-zero CO_2 emissions. *Nat. Commun.* **12**, 6096 (2021).
33. Ou, Y. et al. Deep mitigation of CO_2 and non-CO_2 greenhouse gases toward 1.5 °C and 2 °C futures. *Nat. Commun.* **12**, 6245 (2021).
34. *The Global Methane Pledge* (Climate & Clean Air Coalition, 2021); https://www.globalmethanepledge.org/
35. Herrero, M. et al. Greenhouse gas mitigation potentials in the livestock sector. *Nat. Clim. Change* **6**, 452–461 (2016).
36. Clark, M. A. et al. Global food system emissions could preclude achieving the 1.5° and 2 °C climate change targets. *Science* **370**, 705–708 (2020).
37. Harmsen, M. et al. The role of methane in future climate strategies: mitigation potentials and climate impacts. *Clim. Change* https://doi.org/10.1007/s10584-019-02437-2 (2019).
38. Iyer, G. et al. The role of carbon dioxide removal in net-zero emissions pledges. *Energy Clim. Change* https://doi.org/10.1016/j.egycc.2021.100043 (2021).
39. *The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050* (United States Department of State, 2021); https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf
40. Fuhrman, J. et al. The role of direct air capture and negative emissions technologies in the shared socioeconomic pathways towards +1.5 °C and +2 °C futures. *Environ. Res. Lett.* https://doi.org/10.1088/1748-9326/ac2db0 (2021).
41. Roy, J. et al. 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 Masson-Delmotte, V. et al.) Ch. 5, (Cambridge Univ. Press, 2018).
42. Fuss, S. et al. Moving toward net-zero emissions requires new alliances for carbon dioxide removal. *One Earth* **3**, 145–149 (2020).
43. Fuhrman, J. et al. Food–energy–water implications of negative emissions technologies in a +1.5 °C future. *Nat. Clim. Change* **10**, 920–927 (2020).
44. Fuhrman, J., McJeon, H., Doney, S. C., Shobe, W. & Clarens, A. F. From zero to hero?: why integrated assessment modeling of negative emissions technologies is hard and how we can do better. *Front. Clim.* https://doi.org/10.3389/fclim.2019.00011 (2019).
45. Edmonds, J., Forrister, D., Clarke, L., de Clara, S. & Munnings, C. *The Economic Potential of Article 6 of the Paris Agreement and Implementation Challenges* (IETA, 2019); https://www.ieta.org/resources/International_WG/Article6/CLPC_A6%20report_no%20crops.pdf
46. Purohit, P., Borgford-Parnell, N., Klimont, Z. & Höglund-Isaksson, L. Achieving Paris climate goals calls for increasing ambition of the Kigali Amendment. *Nat. Clim. Change* **12**, 339–342 (2022).
47. Iyer, G. et al. Diffusion of low-carbon technologies and the feasibility of long-term climate targets. *Technol. Forecast. Soc. Change* **90**, 103–118 (2015).
48. Iyer, G. et al. Improved representation of investment decisions in assessments of CO_2 mitigation. *Nat. Clim. Change* **5**, 436–440 (2015).
49. Tong, D. et al. Geophysical constraints on the reliability of solar and wind power worldwide. *Nat. Commun.* **12**, 6146 (2021).
50. Fuss, S. et al. Negative emissions—Part 2: Costs, potentials and side effects. *Environ. Res. Lett.* https://doi.org/10.1088/1748-9326/aabf9f (2018).
51. Brutschin, E. et al. A multidimensional feasibility evaluation of low-carbon scenarios. *Environ. Res. Lett.* https://doi.org/10.1088/1748-9326/abf0ce (2021).
52. IPCC *Climate Change 2022: Mitigation of Climate Change* (eds Shukla, P. R. et al.) (Cambridge Univ. Press, 2022).
53. Pebesma, E. Simple features for R: standardized support for spatial vector data. *R. J.* **10**, 439–446 (2018).
54. Ou, Y. Source code for reproducing Fig5 (map) in Iyer & Ou, et al. 2022 Ratcheting of climate pledges needed to limit peak global warming. *Zenodo* https://doi.org/10.5281/zenodo.7082257 (2022).

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

https://doi.org/10.1038/s41558-022-01508-0

Methods

The Global Change Analysis Model

GCAM is an open-source model developed and maintained at the Pacific Northwest National Laboratory's Joint Global Change Research Institute. In this study, we use the version of the GCAM (v.5.3) used in ref. [5] and available in a public repository[55]. The full documentation of the model is available at the GCAM documentation page (http://jgcri.github.io/gcam-doc/) and the description here is a summary of the online documentation and based on refs. [5,56–59].

GCAM includes representations of five systems: economy, energy, agriculture and land-use, water and climate in 32 geopolitical regions across the globe and the associated land allocation, water use and agriculture production across 384 land subregions and 235 water basins. GCAM operates in 5-year time-steps from 2015 (calibration year) to 2100 by solving for the equilibrium prices and quantities of various energy, agricultural, water, land-use and GHG markets in each time period and in each region. GCAM is a dynamic recursive model. Hence, solutions for each modelling period only depend on conditions in the last modelling period. Outcomes of GCAM are driven by exogenous assumptions about population growth, labour participation rates and labour productivity in the 32 geopolitical regions, along with representations of resources, technologies and policy. GCAM tracks emissions of 24 gases, including GHGs, short-lived species and ozone precursors, endogenously based on the resulting energy, agriculture and land-use systems as discussed in the following subsections.

The GCAM energy system contains representations of fossil resources (coal, oil and gas), uranium and renewable sources (wind, solar, geothermal, hydro and biomass and traditional biomass) along with processes that transform these resources to final energy carriers (electricity generation, refining, hydrogen production, gas processing and district heat), which are ultimately used to deliver goods and services demanded by end-use sectors (residential buildings, commercial buildings, transportation and industry). Each of the sectors in GCAM include technological detail. For example, the electricity generation sector includes several different technology options to convert coal to electricity such as pulverized coal with and without carbon capture and storage (CCS) and coal integrated gasification combined cycle (IGCC) with and without CCS. In every sector within GCAM, individual technologies compete for market share on the basis of the levelized cost of a technology. The cost of a technology in any period depends on (1) its exogenously specified non-energy cost, (2) its endogenously calculated fuel cost and (3) any cost of emissions, as determined by the climate policy. The first term, non-energy cost, represents capital, fixed and variable operation and maintenance costs incurred over the lifetime of the equipment (except for fuel or electricity costs), expressed per unit of output. For example, the non-energy cost of coal-fired power plant is calculated as the sum of overnight capital cost (amortized using a capital recovery factor and converted to dollars per unit of energy output by applying a capacity factor), fixed and variable operations and maintenance costs. The second term, fuel or electricity cost, depends on the specified efficiency of the technology, which determines the amount of fuel or electricity required to produce each unit of output, as well as the cost of the fuel or electricity. The various data sources and assumptions are documented in the GCAM documentation page (http://jgcri.github.io/gcam-doc/).

The prices of fossil fuels and uranium are calculated endogenously. Fossil fuel resource supply in GCAM is modelled using graded resource supply curves that represent increasing cost of extraction as cumulative extraction increases. Wind and rooftop PV technologies include resource costs that are also calculated from exogenous supply curves that represent marginal costs that increase with deployment, such as long-distance transmission line costs that would be required to produce power from remote wind resources. Utility-scale solar photovoltaic and concentrated solar power technologies are assumed to have constant marginal resource costs regardless of deployment levels.

In GCAM, technology choice is determined by market competition. The market share captured by a technology increases as its costs decline but GCAM uses a logit model of market competition. This approach is designed to represent decision-making among competing options when only some characteristics of the options can be observed[60,61] and avoids a 'winner takes all' response.

The agriculture and land-use component of GCAM represents competition for land among alternative uses in 283 agro-economic zones within the 32 regions. Land is allocated between alternative uses such as food crops (including wheat, corn, rice, root and tuber and other grain), commercial biomass, forests, pasture, grassland and shrubs based on expected profitability according to a logit-share mechanism similar to the energy system. The profitability in turn depends on the productivity of the land-based product (for example, mass of harvestable product per hectare), product price and non-land costs of production (labour, fertilizer and so on). The productivity of land-based products is subject to change over time based on future estimates of crop productivity change. GCAM also tracks land from desert, tundra and urban land. However, these are excluded from economic competition and assumed to be fixed over time. Yields for all crops are assumed to improve over time. These improvement rates vary by region, with higher improvement rates in developing regions. The energy system and the agriculture and land-use systems are hard linked (coupled in code). Commercial biomass is demanded in the energy system while its supply is modelled in the agriculture and land-use component. Fertilizer supply is represented in the energy system while fertilizer demand is modelled in the agriculture and land-use system. Traditional biomass is not modelled in the agriculture and land-use system but is instead represented through exogenous supply curves that account for the opportunity cost associated with collecting traditional biomass—collecting traditional biomass requires labour which becomes increasingly expensive as incomes rise.

GCAM tracks emissions of a variety of GHG species: CO_2, CH_4, N_2O, HFCs (HFC23, HFC32, HFC125, HFC134a, HFC143a, HFC152a, HFC227ea, HFC43, HFC236fa, HFC365mfc and HFC245fa), PFCs (CF4 and C2F6) and SF6. The CO_2 emissions result from direct combustion of fossil fuels and conversion to other forms. Once a fossil fuel is extracted, the carbon in the fuel is either emitted or sequestered. The total CO_2 emissions in the base year of GCAM (currently 2015) is calibrated to the Carbon Dioxide Information Analysis Center database[62] at the global level and fossil fuel consumption in the base year is calibrated to the International Energy Agency's Energy Balances Database[63]. Global average emissions coefficients (for example, CO_2 per GJ) are derived from the ratio of the total emissions and the total fuel consumption for each fossil fuel (coal, oil and gas). In each model period, CO_2 emissions from a technology are calculated as the product of global average emission coefficients obtained above and fuel consumption by that technology in that period. Agriculture and land-use change emissions depend on the amount of land-use change, the equilibrium carbon density of the ecosystem and region-specific growth profiles[64].

GCAM also tracks non-CO_2 emissions from the energy and agricultural and land-use systems. Historical emissions of CH_4, N_2O and F-gases are harmonized with the 2019 US Environmental Protection Agency (EPA) Global Non-CO_2 Greenhouse Gas Emission Projections and Mitigation Potential report[65]. Historical emissions of short-lived forcing agents (BC and OC) and air pollutants (SO_2, NO_x and $PM_{2.5}$) are calibrated to the Community Emissions Data System[66]. These historical emissions are then used to develop emission factors (emission per energy input or service output of a specific technology). Emissions factors are assumed to change over time if air pollution controls are tightened (local air pollutants only) or a carbon price is applied (GHGs only; not all sectors). Future emissions are estimated as the product of the projected economic activity, the corresponding emission factor for a given technology and emissions reductions estimated through marginal abatement cost (MAC) curves. MAC curves are based on ref. [65].

https://doi.org/10.1038/s41558-022-01508-0

In our pathways, non-CO_2 emissions can be controlled by two mechanisms. First, changes in activity (phasing out of carbon-intensive fuels due to climate policy) will reduce non-CO_2 emissions (for example, fugitive CH_4 from natural gas production). Second, for emission sources without explicit representation of the underlying activity, emission reductions are calculated off of MAC curves that are parametrized to abatement technologies and abatement levels. MAC curves represent the mitigation cost and corresponding emission reductions achievable for each region, species and available source categories over time.

The version of GCAM used in this study includes important recent technological and socioeconomic trends. First, the effect of COVID-19 on the global economy is reflected by incorporating the latest country-specific International Monetary Fund GDP growth projections[67]. Second, electric power technology cost assumptions (capital cost, operation and maintenance cost and efficiency) follow recent trends and projections and are based on the 2019 National Renewable Energy Laboratory (NREL) Annual Technology Baseline[68]. These assumptions entail substantial capital and operation and maintenance cost reductions for most technologies, especially solar and wind technologies. Third, the version of GCAM used in this study includes electrification options in the transportation sector including electric vehicles and electric trucks. Our transportation cost and energy intensity assumptions are based on the NREL Electrification Futures Study[69].

The version of GCAM used in this study assumes the availability of three CDR options: afforestation, BECCS and DAC technologies. The scale of each option is determined by economics. Our pathways incentivize afforestation by assuming a gradual transition—by 2050—to a regime in which CO_2 emissions from land-use changes are valued at the same price as emissions from the energy system[59,70]. As described earlier, in GCAM, bioenergy competes for land with other land uses on the basis of profitability. BECCS technologies are deployed in a variety of sectors within the GCAM energy system including refining, electricity generation and hydrogen production. Our assumptions for DAC technologies are documented in Supplementary Table 4 and refs. [43,40].

Hector
Hector is the reduced-form carbon-cycle climate module that is available for use in GCAM[15,71] and is an open-source model. This study is based on Hector v.2.5. Hector has a three-part carbon cycle: one-pool atmosphere, three-pool land and four-pool ocean. The model's terrestrial carbon cycle includes primary production and respiration fluxes while also accommodating arbitrary geographic divisions, such as ecological biomes or political units. Hector's ocean component includes a detailed representation of the inorganic carbon cycle, calculating air–sea fluxes and ocean pH (ref. [71]). Hector reproduces the global historical trends of atmospheric CO_2, radiative forcing and surface temperatures.

GCAM interacts with Hector through emissions. At every time step, emissions from GCAM are passed to Hector. Hector then converts these emissions to concentrations when necessary and calculates the associated radiative forcing, as well as the response of the climate system (for example, surface temperature and carbon fluxes).

Emissions pathways
The representation of the NDCs in our central pathway is based on ref. [5] and is explained in detail in the supplementary information to that study. This study also includes 21 new and/or updated NDCs after 30 September 2021, including those from China, Pakistan and many African and Middle Eastern countries that were not included in ref. [5] (Supplementary Table 5). We assume that the NDCs are achieved as stipulated and focus on the climate outcomes of their successful implementation. Examining the likelihood of individual regions achieving their submitted targets is beyond the scope of this study.

Our representation includes only ratified and quantifiable unconditional NDC commitments, including absolute emissions limit, percentage emission reductions from a given reference level and emission intensity targets. Parties whose commitments included: (1) only actions/policies, (2) non-GHG targets with no corresponding GHG emissions target or (3) only sector-specific GHG emissions reduction targets without attempting to quantify the impact on their overall GHG footprints are assumed to have target year emissions equal to the GCAM emissions in the default reference scenario without any climate policy ('Reference—No Policy' in ref. [5]). Likewise, in cases where a country's 2025 and 2030 emissions based on its NDC are lower than the default reference scenario in the same year, the NDC emissions are assumed to be achieved as stipulated. In cases where a country's NDC emissions are higher, emissions are assumed to be equal to the reference scenario. For countries that included multiple types of commitments in their NDCs, such as economy-wide emissions reductions backed by sectoral policies or targets, only the broadest commitment was considered. For example, China's NDC representation in GCAM is based on its commitment to reduce its carbon intensity of GDP by 65% relative to 2005 and it does not explicitly model its targets for non-fossil energy consumption or increased forest stock.

Similar to ref. [5], our pathways include LTSs and net-zero pledges. For countries with LTSs that are different from a net-zero pledge (for example, Mexico), emissions are assumed to meet their NDC commitments in 2030 first. Beyond 2030, emissions linearly reduce to the LTS in the specified target year and then continue to follow a path defined by the decarbonization rate between 2015 and the LTS target year. For countries with net-zero pledges, emissions are assumed to meet their NDC commitments in 2030 first. Beyond 2030, emissions linearly reduce to net-zero in the target year and then remain constant afterwards. In the cases where countries have explicitly committed to net-zero CO_2 emissions, such as South Korea, only CO_2 emissions are constrained. This study also includes additional net-zero pledges that were announced after the completion of the ref. [5] study. These include pledges from India, Brazil, Australia, New Zealand and Argentina (Supplementary Table 2). Where the scope of net-zero targets is somewhat unclear (as in the case of Japan) or in cases where countries use terms such as 'carbon neutral' and 'net-zero GHG emissions' interchangeably, we follow the CAT assessment and assume a net-zero GHG target. For example, China announced a 'carbon neutrality' goal by 2060, which is assumed as a net-zero GHG emission target in our main analysis. This assumption is consistent with latest official interpretations of China's net-zero pledge[72].

Our post-2030 decarbonization rate assumptions are consistent with refs. [57,5]. However, our definition of decarbonization rate is based on all GHGs while the definitions used by ref. [57,5] are based only on fossil fuel and industrial CO_2 emissions (note that the emissions scenarios modelled in the studies of refs. [57,5] do include concurrent reductions in non-CO_2s in response to CO_2 reductions that are facilitated by the decarbonization rate assumptions). Our central assumption about the post-2030 minimum decarbonization rate is 2% and our sensitivity assumptions are 5% and 8%. While the 2% rate has been achieved routinely in history and represents a moderate level of post-2030 mitigation, the 5% and 8% decarbonization rate assumptions can be considered as requiring more dedicated, stringent mitigation policies (Supplementary Fig. 14). For additional context, the 2% decarbonization rate falls under the higher end of the distribution of decarbonization rates implied in the 'baseline' scenarios assessed by the Intergovernmental Panel on Climate Change (IPCC) Special Report on 1.5 °C (SR1.5) and the 5% and 8% assumptions lie at the peak of the distribution of decarbonization rates in scenarios limiting global warming to 1.5 °C (Supplementary Figs. 15 and 16)[18]. We note that 2% minimum decarbonization rate assumption is not binding for any region since the implied 2015–2030 decarbonization rate in the NDCs for all regions is >2% (Supplementary Table 6).

Notably, there is some interaction and overlap among the three strategies explored in this study that countries might use to ratchet ambition. With higher 2030 ambition, the post-2030 minimum decarbonization rate assumption might no longer be binding in some cases. For example, in the case of India, the 2015–2030 decarbonization rates in the pathways with the NDC, NDC+ and NDC++ emission levels in 2030 are, respectively, 2.1%, 4.4% and 4.4% (see Supplementary Table 6 for 2015–2030 decarbonization rates under the NDC, NDC+ and NDC++ emission levels in 2030). Hence, the 2% post-2030 minimum decarbonization rate assumption would be binding only in the NDC cases. In addition, advancing the timing of the net-zero pledges (for countries with net-zero pledges) would result in higher post-2030 decarbonization rates. However, it is important to note that our minimum decarbonization rate assumptions (2%, 5% and 8%) do not affect the emission pathways of countries with net-zero pledges since these countries are always assumed to achieve their pledges—in the specified target years, 5 years in advance or 10 years in advance.

Data availability

Country ratings from the CAT are publicly available at https://climateactiontracker.org/countries/. The latest (v.2020) Human Development Index is publicly available at https://hdr.undp.org/data-center/human-development-index#/indicies/HDI. The datasets generated during and analysed in the current study are available from a public repository (https://doi.org/10.5281/zenodo.7069063). Source data are provided with this paper.

Code availability

GCAM is an open-source community model available at https://github.com/JGCRI/gcam-core/releases. The version of GCAM and additional input files associated with this study are available at https://doi.org/10.5281/zenodo.7069066.

References

55. Ou, Y. Source code and data for Ou et al. 2021 Updates to Paris climate pledges improve chances of limiting global warming to well below 2 °C. *Zenodo* https://doi.org/10.5281/zenodo.5821125 (2021).
56. Iyer, G. et al. Implications of sustainable development considerations for comparability across NDCs. *Nat. Clim. Change* **8**, 124–129 (2018).
57. Fawcett, A. A. et al. Can Paris pledges avert severe climate change? *Science* **350**, 1168–1169 (2015).
58. McJeon, H. et al. Limited impact on decadal-scale climate change from increased use of natural gas. *Nature* **514**, 482–485 (2014).
59. Wise, M. et al. Implications of limiting CO_2 concentrations for land use and energy. *Science* **324**, 1183–1186 (2009).
60. Clarke, J. F. & Edmonds, J. Modelling energy technologies in a competitive market. *Energy Econ.* **15**, 123–129 (1993).
61. McFadden, D. Econometric models for probabilistic choice among products. *J. Bus.* **53**, S13–S29 (1980).
62. Boden, T. A., Marland, G. & Andres, R. J. *Global, Regional, and National Fossil-Fuel CO_2 Emissions* (Carbon Dioxide Information Analysis Center, 2009).
63. *World Energy Balances 2019* (International Energy Agency, 2019).
64. Wise, M., Calvin, K., Kyle, P., Luckow, P. & Edmonds, J. A. E. Economic and physical modeling of land use in Gcam 3.0 and an application to agricultural productivity, land, and terrestrial carbon. *Clim. Change Econ.* **05**, 1450003 (2014).
65. *Global Non-CO_2 Greenhouse Gas Emission Projections & Mitigation 2015–2050* (United States Environmental Protection Agency, 2019).
66. O'Rourke, P. R. et al. CEDS v_2021_04_21 Release Emission Data (v_2021_02_05). *Zenodo* https://doi.org/10.5281/zenodo.4741285 (2021).
67. Real GDP growth (International Monetary Fund, 2021); https://www.imf.org/external/datamapper/NGDP_RPCH@WEO/OEMDC/ADVEC/WEOWORLD
68. Vimmerstedt et al. 2019 *Annual Technology Baseline ATB Cost and Performance Data for Electricity Generation Technologies* (National Renewable Energy Lab, 2019).
69. Jadun et al. *Electrification Futures Study: End-use Electric Technology Cost and Performance Projections through 2050* (National Renewable Energy Lab, 2017).
70. Calvin, K. et al. Trade-offs of different land and bioenergy policies on the path to achieving climate targets. *Clim. Change* **123**, 691–704 (2014).
71. Hartin, C. A., Bond-Lamberty, B., Patel, P. & Mundra, A. Ocean acidification over the next three centuries using a simple global climate carbon-cycle model: projections and sensitivities. *Biogeosciences* **13**, 4329–4342 (2016).
72. *XIE Zhenhua Explains 1+N Policy Framework for the Timeline and Roadmap of China's Carbon Peak and Neutrality Goals* (National Center for Climate Change Strategy and International Cooperation, accessed 4 March 2022); http://www.ncsc.org.cn/xwdt/gnxw/202107/t20210727_851433.shtml

Acknowledgements

The research described in this paper was conducted with support from the US EPA IAA DW-089-92460001 (G.I., Y.O., J.E., J.F., S.W. and H.M.). The views and opinions expressed in this paper are those of the authors alone and do not necessarily state or reflect those of the Environmental Protection Agency or the US Government and no official endorsement should be inferred.

Author contributions

G.I. and Y.O. contributed equally to this study. G.I., Y.O., J.E., A.A.F., N.H. and H.M. designed the research. G.I. wrote the first draft of the paper. Y.O. conducted the simulations. G.I., Y.O., J.E., J.F., S.W. and H.M. contributed to the modelling tools. J.M. contributed to the writing of the paper. All authors contributed to writing the paper.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41558-022-01508-0.

Correspondence and requests for materials should be addressed to Haewon McJeon.

Peer review information *Nature Climate Change* thanks Matthias Weitzel, Ioannis Dafnomilis and Kate Dooley for their contribution to the peer review of this work.