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Expert Report

Federal Court of Australia

Pabai & Anor v Commonwealth of Australia (VID622/2021)

July 2023

Prof. Malte Meinshausen[1]

Geography, Earth and Atmospheric Sciences

The University of Melbourne

Parkville VIC 3052

Preamble and Declaration

1. I have been asked to produce an expert report. My letter of instruction and brief can be found at Annexure A to my report. I have read the brief and responded to all questions asked in it. I have read, understood and complied with the Expert Evidence Practice Note (GPN-EXPT) of the Federal Court and the Harmonized Expert Witness Code of Conduct and agree to be bound by them.

2. In preparing this report, I have been supported by Dr. Zebedee Nicholls who has acted as my research assistant in a number of assignments. Their previous experience (detailed in the curriculum vitae in Annexure C) has given them the knowledge of the subject matter for them to effectively provide that support under my close supervision and direction. All opinions expressed herein are my own and are based wholly or substantially on my specialised knowledge arising from my training and experience as a climate scientist.

3. I have made all inquiries which I believe are desirable and appropriate and no matters of significance which I regard as relevant have, to my knowledge, been withheld from the Court. I have referenced all assumptions and material facts on which my opinions are based throughout my report.

4. Given the length of the report, I have included a brief summary at the beginning of the report.

[1] Note that my given names as per my passport are ALEXANDER MALTE, but my scientific and publishing name is MALTE MEINSHAUSEN, with MALTE also being my calling name.

SUMMARY

5. In this report, I examine Australia's remaining cumulative greenhouse gas emissions consistent with limiting global-mean temperature increase to 1.5°C above pre-industrial levels. I begin with the global CO_2 budget consistent with limiting global-mean temperature increase to 1.5°C above pre-industrial levels, then move to corresponding global remaining cumulative greenhouse gas emissions consistent with this CO_2 budget.

6. Having established the cumulative greenhouse gas emissions consistent with 1.5°C warming, I then consider Australia's share of cumulative greenhouse gas emissions in the light of different methodologies for allocating shares to countries. The major motivation for considering country shares is The Paris Agreement. The Paris Agreement is an agreement between all parties to the United Nations Framework Convention on Climate Change (UNFCCC), of which Australia is one, with a number of stated aims including holding 'the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels'[2]. The Paris Agreement also includes a commitment by countries that the 'Agreement will be implemented to reflect equity and the principle of common but differentiated responsibilities and respective capabilities, in the light of different national circumstances'[3], including in terms of greenhouse gas emission reductions. In the literature that has considered how to implement the agreement in terms of the action each country should take and how to allocate shares of global cumulative greenhouse gas emissions to countries, three broad categories of methodologies are used. The first is grandfathering, which maintains the current distribution of emissions and allocates greater shares to countries with high emissions today. The second is equality or equal per capita, where future emission shares are allocated equally to all people hence on a population basis to countries. The third is a set of methodologies based on accounting for historical responsibility for climate change and the ability to transition each country's economy to net zero (capacity is typically measured in terms of GDP per capita). This last category typically allocates smaller shares to countries with high current and past emissions and countries with larger GDP.

7. I calculate limits on Australia's remaining cumulative greenhouse gas emissions until 2050 consistent with limiting global-mean temperature increase to 1.5°C above pre-industrial levels under implementations representative of each category of allocation methodologies. In all cases, I find that Australia's 2030 targets are not and have not been consistent with remaining within its share of remaining cumulative greenhouse gas emissions. The only exception to this is if I assume that Australia receives a share at the high-end of range seen in the literature, in which case the current target of 43% is consistent with Australia's share of remaining cumulative greenhouse gas emissions but

[2] Article 2.1(a), United Nations (2015). The Paris Agreement. Available at https://unfccc.int/sites/default/files/english_paris_agreement.pdf, last accessed 10 July 2023.
[3] Article 2.2, United Nations (2015). The Paris Agreement. Available at https://unfccc.int/sites/default/files/english_paris_agreement.pdf, last accessed 10 July 2023.

only if, after 2030, Australia transitions to net zero with minimal further emissions (if a straight-line path to net zero emissions is followed, Australia would have to reach net zero two years later i.e. by the start of 2033). Under the equality and historical responsibility allocation methods, as at 2022 Australia had already exhausted its remaining cumulative greenhouse gas emissions consistent with limiting global-mean temperature increase to 1.5°C above pre-industrial levels.

Basis of expertise

Q.1 Please describe your academic qualifications and professional background and any other training, study or experience that is relevant to your answering the questions in this Annexure. You may wish to do so by reference to a current curriculum vitae.

8. My CV is attached at Annexure B.

9. I am currently a Professor at the University of Melbourne where I teach the Masters subjects *Climate Modelling and Climate Change* and *Climate Science for Decision Making*. I hold a Ph.D. in "Climate Science & Policy" from the Swiss Federal Institute of Technology (ETH Zurich) and an M.Sc. in "Environmental Change and Management" from the University of Oxford. Climate Science refers to the study of the climate system: its composition, how energy and matter flow within it, the carbon cycle and their sensitivities to external and internal drivers both natural and anthropogenic. Those anthropogenic drivers are mainly anthropogenic CO_2 and other greenhouse gas emissions.

10. I was one of the lead authors of the most recent Working Group I (Physical Climate Science) contribution to the Intergovernmental Panel on Climate Change's (IPCC's) Sixth Assessment Report (AR6), contributing author to the IPCC Working Group III (Mitigation Science) of AR6 and I was also a core writing team member of the IPCC AR6 Synthesis Report. My main research activity relates to carbon budgets, climate scenarios and the reduced-complexity model MAGICC. I founded the Climate & Energy College at the University of Melbourne (climatecollege.unimelb.edu.au) and was its Director for the first five years, as well as the Co-Director of the Energy Transition Hub (www.energy-transition-hub.org). In my field of climate science, climate scenarios and remaining carbon budgets, I have been awarded highly-cited researcher status, being one of three scientists having received that status in the Faculty of Science at the University of Melbourne in 2022.

11. Before coming to The University of Melbourne, I was a senior researcher at the Potsdam Institute for Climate Impact Research (PIK) from 2006 to 2011. Previously, I obtained a postdoctoral fellowship at the National Center for Atmospheric Research in Boulder, Colorado. I was a contributing author to the Fourth and Fifth Assessment Reports of the IPCC and the Special Report on 1.5°C. In 2013, I received a Future Fellowship Award to investigate Australia's fair contribution towards the global climate change mitigation effort. From 2005 to 2017, I was a scientific advisor to the German Environmental Ministry related to international climate change negotiations under the UNFCCC.

12. I have been involved in carbon and emissions budget calculations over many years. Most recently, I was part of the team that assessed carbon budgets in Chapter 5 of the IPCC's AR6. My key responsibility was contributing to the quantification of the impact of non-CO_2 emissions under multiple scenarios, ensuring that they were adequately captured and reflected in the carbon budget assessment.

13. I have also assessed emissions pledges from countries over many years, including consideration of how the pledged emissions split between different greenhouse gases and how offsets and carbon credits are accounted for. This work was featured in April 2022 in the cover story of the scientific journal NATURE[4]. In the UNFCCC climate negotiations from 2005 to 2017, as part of the German and European negotiation teams, I was also involved in the design of some accounting frameworks under the Kyoto Protocol. Such work requires the ability to consider issues of double-counting, additionality, permanence, leakage, and a clear understanding of the sources of greenhouse gases across a range of applications, including the distinction between CO_2 and other greenhouse gas emissions. I published on metrics and their use - comparing CO_2 and non-CO_2 gases and recently presented this research within a UNFCCC-IPCC workshop[5]. I have also published research on questions related to quantifying climate equity, specifically how different views of equity can be quantified and what these different views mean for different country's emissions budgets and emissions reduction targets[6,7].

[4] Meinshausen, M., Lewis, J., McGlade, C. *et al.* Realization of Paris Agreement pledges may limit warming just below 2 °C. *Nature* **604**, 304–309 (2022). https://doi.org/10.1038/s41586-022-04553-z

[5] https://unfccc.int/event/ipcc-in-session-technical-workshop-on-findings-on-emission-metrics-contained-in-its-sixth-assessment

[6] Meinshausen, M., Jeffery, L., Guetschow, J., Robiou du Pont, Y., Rogelj, J., Schaeffer, M., Höhne, N., den Elzen, M., Oberthür, S., & Meinshausen, N. (2015). National post-2020 greenhouse gas targets and diversity-aware leadership. *Nature Climate Change*, *5*(12), 1098-1106. https://doi.org/10.1038/nclimate2826

[7] Robiou du Pont, Y., & Meinshausen, M. (2018). Warming assessment of the bottom-up Paris Agreement emissions pledges. *Nature Communications*, *9*(1), 4810. https://doi.org/10.1038/s41467-018-07223-9

The global CO_2 budget

Q.2 Please explain what a CO_2 Budget is.

14. The scientific basis of the CO_2 budget concept was a series of papers published in 2008 and 2009[8,9,10,11,12]. These papers showed that there was, to a good approximation[13], a linear relationship between total emissions of CO_2 and global-mean warming. Put simply, each tonne of CO_2 that is emitted causes the same amount of warming from the point of its emission for thousands of years into the future. As a result, the total warming that humans cause via anthropogenic CO_2 emissions only depends on how much CO_2 is emitted in total over a given period of time and does not depend on when exactly that CO_2 was emitted. This realisation means that, if we as a society want to halt global warming below a given level, there is a maximum amount of CO_2 we can emit i.e. we can define a budget (and, to a first order approximation[14], it doesn't matter whether we use our budget up all at once or bit by bit).

15. The IPCC has used the CO_2 budget concept since its Fifth Assessment Report (AR5), published over 2013 and 2014 (the reports are made up of multiple parts, hence are often published over multiple years). It was then used again in the IPCC's Special Report on Global Warming of 1.5°C, published in 2018, and in the IPCC's Sixth Assessment Report (AR6), published over 2021 to 2023. For context, the IPCC is a UN body which assesses the available science and produces reports based on this assessment. Every 5-10 years, the IPCC produces assessment reports, which examine the state of the science and summarise it based on the expert assessment of its authors. The reports are written by hundreds of scientific authors, reviewed by any interested

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[8] Allen, M. R., Frame, D. J., Huntingford, C., Jones, C. D., Lowe, J. A., Meinshausen, M., & Meinshausen, N. (2009). Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature*, *458*(7242), 1163.

[9] Meinshausen, M., Meinshausen, N., Hare, W., Raper, S. C. B., Frieler, K., Knutti, R., Frame, D. J., & Allen, M. R. (2009). Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature*, *458*(7242), 1158-1162. https://doi.org/10.1038/nature08017

[10] Matthews, H. D., & Caldeira, K. (2008). Stabilizing climate requires near-zero emissions. *Geophysical Research Letters*, *35*(4). https://doi.org/10.1029/2007GL032388

[11] Matthews, H. D., Gillett, N. P., Stott, P. A., & Zickfeld, K. (2009). The proportionality of global warming to cumulative carbon emissions. *Nature*, *459*(7248), 829.

[12] Zickfeld, K., Eby, M., Matthews, H. D., & Weaver, A. J. (2009). Setting cumulative emissions targets to reduce the risk of dangerous climate change. *Proceedings of the National Academy of Sciences*, *106*(38), 16129-16134. https://doi.org/10.1073/pnas.0805800106

[13] Here, a good approximation means to within around 15% of the warming that is projected when non-linear terms are also included, see e.g. Figure 1(e) Nicholls, Z. R. J., Gieseke, R., Lewis, J., Nauels, A., & Meinshausen, M. (2020). Implications of non-linearities between cumulative CO_2 emissions and CO_2-induced warming for assessing the remaining carbon budget. *Environmental Research Letters, 15*(7), 074017. https://doi.org/10.1088/1748-9326/ab83af.

[14] The impact of releasing the CO_2 at different times, e.g. all at once instead of gradually over time, on warming is around 10%. See Figure 4(d). Nicholls, Z. R. J., Gieseke, R., Lewis, J., Nauels, A., & Meinshausen, M. (2020). Implications of non-linearities between cumulative CO_2 emissions and CO_2-induced warming for assessing the remaining carbon budget. *Environmental Research Letters, 15*(7), 074017. https://doi.org/10.1088/1748-9326/ab83af.

party who registers as a reviewer (including many from governments around the world, with all comments being individually responded to) and approved by governments before being published (with the Summary for Policy Makers in each part coming under particularly strong scrutiny and being subject to line-by-line approval before publication). As a result, these assessment reports are the most authoritative summaries of the available science on climate change.

Definition

16. A CO_2 budget is the maximum amount of CO_2 that can be emitted while keeping global-mean temperature rise below a given threshold. When the budget refers only to future emissions, it is typically referred to as a 'remaining budget'. For example, the remaining CO_2 budget for keeping warming below 1.5°C relative to 1850-1900 in the latest IPCC report was 500 $GtCO_2$ from the start of 2020 onwards. Here, $GtCO_2$ is gigatonne of CO_2 i.e. one billion tonnes of CO_2 or one trillion kilograms of CO_2. I also use $MtCO_2$, which is a megatonne of CO_2 i.e. one million tonnes of CO_2 or one billion kilograms of CO_2. 1 $GtCO_2$ is equal to 1000 $MtCO_2$.

Subtleties

17. The budget concept is principally simple. However, there are subtleties which are important to understand and keep in mind when discussing budgets. In the rest of this section I discuss subtleties relevant to the questions I have been asked.

18. Budgets are mostly discussed as 'remaining' budgets from a particular point in time. For example, the IPCC's 500 $GtCO_2$ budget is a budget for emissions from the start of 2020. Since the start of 2020, humans have emitted around 135 $GtCO_2$ so the budget from today would be around 365 $GtCO_2$ (although this number is a tentative estimate due to a lack of real-time emissions data). Moving in the other direction, humans emitted around 200 $GtCO_2$ between the start of 2015 and the start of 2020 so the budget from the start of 2015 would have been around 700 $GtCO_2$.

19. The CO_2 budget concept applies to the globe as a whole. As discussed previously, there is a near-linear relationship between global-mean warming and global total CO_2 emissions and it does not matter where the CO_2 emissions occur or when they occurred: each tonne increases global-mean temperatures and increases them by roughly the same amount.

20. There is some uncertainty in exactly how much warming each tonne of CO_2 emissions causes. This uncertainty is addressed in the communication of carbon budgets by associating a given budget with a likelihood to stay below a certain warming level. So, rather than calculating a budget that results in one specific warming level, it is common to instead calculate a budget that keeps warming below a threshold with a given probability. For example, the budget that has a 50% chance of keeping warming below 1.5°C. In this case, if humanity emits the full budget, there is a 50% chance (based on

current scientific knowledge) that global-mean temperatures will stay below 1.5°C. If humanity emits less than the full budget, the odds of staying below 1.5°C will be greater than 50%. If humanity emits more than the budget, the odds of staying below 1.5°C will be less than 50%.

21. The next subtlety is the reference period against which warming is assessed. Warming must be given relative to a time period, for example 2000-2020, 1961-1990, 1850-1900 or pre-industrial. Typically, warming is given relative to a time period of multiple decades in order to avoid the effects of natural variability which can make a single year or group of years much warmer or colder than the preceding or following years and aren't a good representation of the impact of anthropogenic emissions. In most of its reports, the IPCC expresses warming relative to 1850-1900. However, The Paris Agreement explicitly refers to 'pre-industrial levels'[15]. These two are not necessarily identical and the difference should be accounted for when calculating CO_2 budgets and derived quantities.

22. The relationship between warming and cumulative CO_2 emissions is very close to linear[16,17,18,19,20,21]. However, this linearity arises due to a combination of non-linear relationships. Specifically, the relationship between CO_2 emissions and CO_2 concentrations is super-linear, i.e. each tonne of CO_2 emissions causes a greater increase in atmospheric CO_2 concentrations than the last. The super-linearity is largely due to feedbacks in the climate system. In contrast, the relationship between atmospheric CO_2 concentrations and warming is sublinear. In other words, each increase in atmospheric CO_2 concentrations causes a smaller increase in warming than the previous increment. The combination of these super- and sublinear relationships is what leads to a linear relationship between cumulative CO_2 emissions and warming. When discussing the linear relationship between warming and emissions, the emissions are defined as only anthropogenic emissions.

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[15] Article 2.1(a), United Nations (2015). The Paris Agreement. Available at https://unfccc.int/sites/default/files/english_paris_agreement.pdf, last accessed 10 July 2023.

[16] Allen, M. R., Frame, D. J., Huntingford, C., Jones, C. D., Lowe, J. A., Meinshausen, M., & Meinshausen, N. (2009). Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature*, *458*(7242), 1163.

[17] Meinshausen, M., Meinshausen, N., Hare, W., Raper, S. C. B., Frieler, K., Knutti, R., Frame, D. J., & Allen, M. R. (2009). Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature*, *458*(7242), 1158-1162. https://doi.org/10.1038/nature08017

[18] Matthews, H. D., & Caldeira, K. (2008). Stabilizing climate requires near-zero emissions. *Geophysical Research Letters*, *35*(4). https://doi.org/10.1029/2007GL032388

[19] Matthews, H. D., Gillett, N. P., Stott, P. A., & Zickfeld, K. (2009). The proportionality of global warming to cumulative carbon emissions. *Nature*, *459*(7248), 829.

[20] Zickfeld, K., Eby, M., Matthews, H. D., & Weaver, A. J. (2009). Setting cumulative emissions targets to reduce the risk of dangerous climate change. *Proceedings of the National Academy of Sciences*, *106*(38), 16129-16134. https://doi.org/10.1073/pnas.0805800106

[21] Nicholls, Z. R. J., Gieseke, R., Lewis, J., Nauels, A., & Meinshausen, M. (2020). Implications of non-linearities between cumulative CO_2 emissions and CO_2-induced warming for assessing the remaining carbon budget. *Environmental Research Letters, 15*(7), 074017. https://doi.org/10.1088/1748-9326/ab83af

23. There are multiple flows of carbon between the atmosphere, biosphere and oceans. Some of these are directly caused by humans i.e. are anthropogenic, such as burning of fossil fuels or deforestation. Others are mainly natural, such as the fluxes associated with the seasonal growth and decay of plants. Some of these fluxes are difficult to categorise because of interplay between the anthropogenic and natural influences, for example the uptake of CO_2 by trees. On the one hand, this process is natural. On the other hand, trees are now taking up more CO_2 than previously and part of that increased uptake is because there is now much more atmospheric CO_2 available to be taken up. These elevated atmospheric CO_2 concentrations are due to humanity's emissions, but they in turn induce more plant growth (CO_2 fertilisation), so that the terrestrial carbon uptake is bigger than it would have been without CO_2 fertilisation. When quantifying emissions, different conventions are followed and these impact how much of the natural fluxes are included in emissions inventories. As discussed in the previous paragraph, when discussing the linear relationship between warming and emissions, the emissions are defined as only anthropogenic emissions. However, when countries report their emissions (e.g. to the UNFCCC), they also include some component of the natural uptake of carbon too (i.e. countries include non-anthropogenic emissions too). Therefore, country reported emissions must be made consistent with the scientific definitions before they can be compared with budgets on a like-for-like basis[22].

24. The final subtlety is one of emissions boundaries. In general, countries only report emissions within their territories in their emissions accounting (e.g. to the UNFCCC) and explicitly exclude emissions from international aviation and shipping. However, these sectors also contribute to climate change and take up some of the budget. This must be accounted for when calculating remaining emissions according to country reporting (as opposed to remaining emissions in total, including those that don't appear in country reports) to avoid setting targets that aren't actually compatible with the budget.

Q.3 How do cumulative greenhouse gas emissions relate to international efforts to limit global temperature increase? Please explain how cumulative greenhouse gas emissions are relevant in the context of a CO_2 budget.

Relevance of cumulative greenhouse gas emissions

25. While the CO_2 budget concept is the most well-known concept, countries generally don't announce targets for CO_2 alone. Instead, they typically announce targets for a basket of emissions that includes non-CO_2 greenhouse gas emissions, the most important of which are methane (CH_4) and nitrous oxide (N_2O). This is also the case for Australia, whose emissions targets apply to the basket of greenhouse gas emissions that comprises the most important gases carbon dioxide (CO_2) and methane (CH_4), but then

[22] Grassi, G., Stehfest, E., Rogelj, J., van Vuuren, D., Cescatti, A., House, J., Nabuurs, G.-J., Rossi, S., Alkama, R., Viñas, R. A., Calvin, K., Ceccherini, G., Federici, S., Fujimori, S., Gusti, M., Hasegawa, T., Havlik, P., Humpenöder, F., Korosuo, A., . . . Popp, A. (2021). Critical adjustment of land mitigation pathways for assessing countries' climate progress. *Nature Climate Change*, *11*(5), 425-434. https://doi.org/10.1038/s41558-021-01033-6

also nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF_6) and nitrogen trifluoride (NF_3)[23], which are the main greenhouse gases that are not controlled under the Montreal Protocol[24]. Greenhouse gas emissions are typically measured in units of CO_2 equivalent, e.g. $MtCO_2$-eq (one million tonnes of CO_2 equivalent) and $GtCO_2$-eq (one billion tonnes of CO_2 equivalent). Australia converts emissions of non-CO_2 greenhouse gases into CO_2 equivalent using the GWP100 metric from the IPCC's Fifth Assessment Report[25] so I also use this metric throughout this report.

26. As almost all countries report targets for greenhouse gas emissions, not CO_2 alone, there is a need to provide information on what greenhouse gas emissions are consistent with given CO_2 budgets and warming limits (with a given chance of staying below those limits). Thus, providing a measure of greenhouse gas emissions, derived from the warming limit and associated CO_2 budget, can - if done properly - provide the link needed between the currency/units in which countries report, and the currency/units most frequently used by the scientific community.

27. Throughout this report, I will mainly write in terms of cumulative greenhouse gas emissions up to a given point in time consistent with a given CO_2 budget. I do this as greenhouse gas emissions are the currency/units of Australia's (and many other nations') emission reduction targets.

Basis for limits on cumulative greenhouse gas emissions

28. In order to understand the implications of countries' emissions pledges, the aforementioned translation of CO_2 budgets into greenhouse gas emissions has to be performed. I will cover those translation steps here and elucidate in the quantitative part of the report.

29. In this context, the key difference between greenhouse gases is how long they remain in the atmosphere after being emitted.

30. CO_2 does not have a finite atmospheric lifetime on the timescales of interest to anthropogenic climate change[26]. Rather, any emitted CO_2 is simply re-distributed among the active carbon pools, which are the atmosphere, the terrestrial biosphere and the

[23] Australia's NDC, available at https://unfccc.int/sites/default/files/NDC/2022-06/Australias%20NDC%20June%202022%20Update%20%283%29.pdf, last accessed July 10 2023
[24] For information on the Montreal Protocol, see e.g. https://www.unep.org/ozonaction/who-we-are/about-montreal-protocol, last accessed July 10 2023
[25] Australia's NDC, available at https://unfccc.int/sites/default/files/NDC/2022-06/Australias%20NDC%20June%202022%20Update%20%283%29.pdf, last accessed July 10 2023
[26] Each individual CO_2 molecule actually cycles through the atmosphere, land and ocean on a relatively short timeline. However, as one molecule leaves the atmosphere, others move in, so the overall stock of CO_2 in the atmosphere changes less than the actual fluxes between the atmosphere, plants and the oceans would suggest. It is the stock of carbon accumulated in the atmosphere which matters for climate change, which is why carbon dioxide is considered to be a long-lived greenhouse gas without a finite lifetime.

oceans. CO_2 can therefore be regarded as a 'long-lived' greenhouse gas, as it does not completely disappear out of the atmosphere - even after thousands of years. This long-lived nature is a key reason (although not the complete story) that every tonne of CO_2 emitted causes the same amount of ongoing warming, irrespective of where or when it was emitted.

31. In the case of methane (CH_4), the second-largest contributor to climate change to date, it has a lifetime of around a decade. As a result, it is referred to as 'short-lived'. The key consequence of its short-lived behaviour is that the warming at any particular point in the future caused by CH_4 emissions does depend on when the CH_4 was emitted. Emitting a certain amount of methane at once has a much larger effect in terms of peak warming than emitting the same amount of methane gradually over a long period. The fact that the warming from methane depends on when it was emitted means that there is no CH_4 equivalent of the CO_2 budget.

32. However, there is a rich literature on how society can reduce its emissions (for example, [27,28,29,30]). In this literature, teams study how humanity can reduce its environmental (specifically climate change) impact and report the emissions associated with such a transition. This literature was assessed in the IPCC's Special Report on 1.5°C and then most recently assessed in the Working Group 3 Contribution (which focuses on mitigation of climate change) to the IPCC's Sixth Assessment Report[31]. This report investigates a range of ways that warming can be limited to certain levels.

33. For the questions I have been asked, the key takeaway from the literature investigated by the IPCC is that there is a linear relationship between the CO_2 budget and cumulative greenhouse gas emissions in scenarios which take steps to reduce greenhouse gas emissions in the cheapest way possible (so-called cost-optimal scenarios). This

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[27] See e.g. Van Vuuren, D.P., Stehfest, E., Gernaat, D.E., Doelman, J.C., Van den Berg, M., Harmsen, M., de Boer, H.S., Bouwman, L.F., Daioglou, V., Edelenbosch, O.Y. and Girod, B., 2017. Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Global Environmental Change*, *42*, pp.237-250.

[28] Rogelj, J., Popp, A., Calvin, K.V., Luderer, G., Emmerling, J., Gernaat, D., Fujimori, S., Strefler, J., Hasegawa, T., Marangoni, G., Krey, V., Kriegler, E., Riahi, K., van Vuuren, D.P., Doelman, J., Drouet, L., Edmonds, J., Fricko, O., Harmsen, M., Havlik, P., Humpenöder, F., Stehfest, E., Tavoni, M., Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nature Climate Change 8*, 2018, 325-332. DOI:10.1038/s41558-018-0091-3

[29] Hasegawa, T. et al., Land-based implications of early climate actions without global net-negative emissions, *Nature Sustainability*, 2021. DOI: doi.org/10.1038/s41893-021-00772-w

[30] Bertram, C. et al., Energy system developments and investments in the decisive decade for the Paris Agreement goals, *Environmental Research Letters*, 2021. DOI: doi.org/10.1088/1748-9326/ac09ae

[31] Riahi, K., R. Schaeffer, J. Arango, K. Calvin, C. Guivarch, T. Hasegawa, K. Jiang, E. Kriegler, R. Matthews, G.P. Peters, A. Rao, S. Robertson, A.M. Sebbit, J. Steinberger, M. Tavoni, D.P. van Vuuren, 2022: Mitigation pathways compatible with long-term goals. 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* [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.005

relationship is most clearly illustrated by Figure 1.29 of the Working Group 1 Contribution to the IPCC's Sixth Assessment Report (reproduced below, see Figure 1).

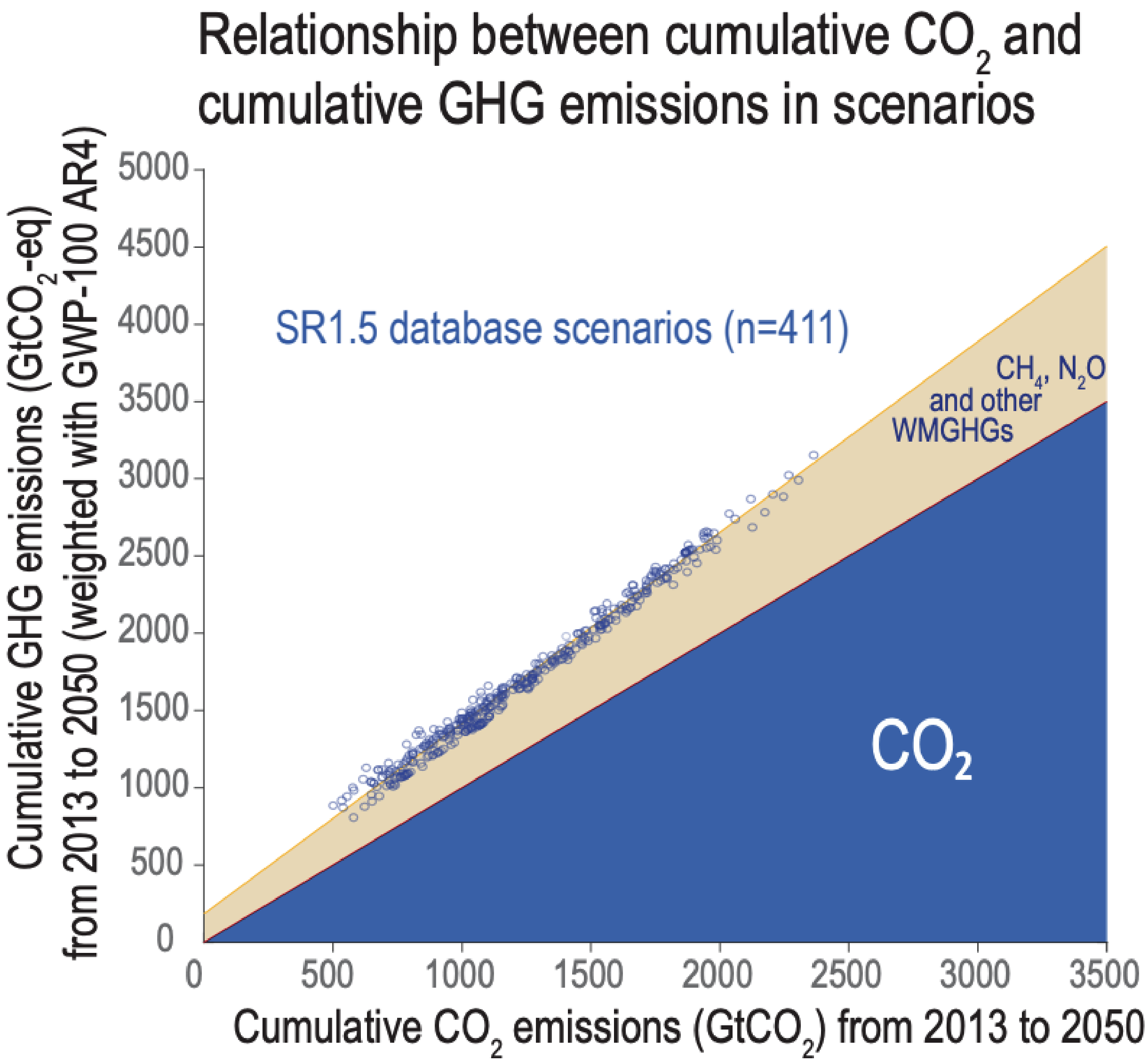

Figure 1 Relationship between cumulative CO_2 emissions and cumulative greenhouse gas emissions in scenarios for the transition to net zero explored by the IPCC's Special Report on 1.5°C. Inset reproduced from Figure 1.29 of AR6 WG1[32]. For a more detailed explanation of the steps being taken here, see Figure 2 which follows the same methodology.

[32] Chen, D., M. Rojas, B.H. Samset, K. Cobb, A. Diongue Niang, P. Edwards, S. Emori, S.H. Faria, E. Hawkins, P. Hope, P. Huybrechts, M. Meinshausen, S.K. Mustafa, G.-K. Plattner, and A.-M. Tréguier, 2021: Framing, Context, and Methods. 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* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T.

34. As a result, if one knows the CO_2 budget or warming limit one is interested in and uses the latest understanding of how society could transition to a net-zero economy, then it is possible to infer the global cumulative greenhouse gas emissions up to a given point in time consistent with that CO_2 budget or warming limit. This observation provides the vital link needed to understand the consistency between greenhouse gas emissions pledges put forward by countries around the world and the well understood science of what is required to stay below given warming limits. A similar translation between CO_2 budgets and greenhouse gas emissions was also performed in work for the Victorian government[33]. The reverse transformation, i.e. translating GHG emission targets back to CO_2 cumulative emissions, is also performed. A prominent example is the UNFCCC Secretariat's Synthesis reports, which considers aggregate global GHG emission levels pursuant to the individual country GHG emission targets[34]. The approach taken in the UNFCCC report is to assume current and projected CO_2 and non-CO_2 emission fractions from IPCC scenarios, which provides the same translation from greenhouse gas emissions to CO_2 - just in reverse.

Subtleties

35. As in the above, there are subtleties that are important to understand when considering these issues. Most importantly, the link between a CO_2 budget and cumulative greenhouse gas emissions is based on the combination of physical science and current understanding of how society can move to net-zero. This relationship is robust in the latest collection of scenarios assessed by the IPCC, namely the AR6 WG3 scenario database[35]. This database includes over 1,200 different scenarios for how future emissions may evolve. It is possible that new technology may lead to new options in the future, and this would require a re-evaluation of this relationship. However, such a re-evaluation would take us outside the range of options considered by the wide collection in AR6.

36. The second subtlety is the need for an endpoint when discussing cumulative greenhouse gas emissions, which is in theory in contrast to CO_2 budgets where there is

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Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 147–286, doi:10.1017/9781009157896.003

[33] https://www.climatechange.vic.gov.au/__data/assets/pdf_file/0029/635168/Victorian-emissions-budgets.pdf

[34] See e.g. UNFCCC Synthesis report on the aggregate effect of the intended nationally determined contributions (FCCC/CP/2015/7), 2015, paragraph 33, 97, available at: https://unfccc.int/resource/docs/2015/cop21/eng/07.pdf

[35] Edward Byers, Volker Krey, Elmar Kriegler, Keywan Riahi, Roberto Schaeffer, Jarmo Kikstra, Robin Lamboll, Zebedee Nicholls, Marit Sanstad, Chris Smith, Kaj-Ivar van der Wijst, Alaa Al Khourdajie, Franck Lecocq, Joana Portugal-Pereira, Yamina Saheb, Anders Strømann, Harald Winkler, Cornelia Auer, Elina Brutschin, Matthew Gidden, Philip Hackstock, Mathijs Harmsen, Daniel Huppmann, Peter Kolp, Claire Lepault, Jared Lewis, Giacomo Marangoni, Eduardo Müller-Casseres, Ragnhild Skeie, Michaela Werning, Katherine Calvin, Piers Forster, Celine Guivarch, Tomoko Hasegawa, Malte Meinshausen, Glen Peters, Joeri Rogelj, Bjorn Samset, Julia Steinberger, Massimo Tavoni, Detlef van Vuuren. AR6 Scenarios Database hosted by IIASA International Institute for Applied Systems Analysis, 2022. doi: 10.5281/zenodo.5886911 | url: data.ece.iiasa.ac.at/ar6/

no end point (whether the budget is spent now or later doesn't matter for peak temperatures). In the very long-term, it is theoretically possible to have ongoing constant methane emissions and no further warming (because the system would reach an equilibrium between the warming from new methane emissions and the decline in warming from previous methane emissions). As a result, the total cumulative methane emissions consistent with a given warming limit could continue to grow without limit. Introducing the end point avoids this issue and is also more relevant for the questions considered here, which focus on emissions over a specific time period.

37. The third subtlety is the constraint implied by the fact that the transition discussed will happen over a timespan of decades with a constrained start and end point. In pathways that limit warming to 1.5°C with no or limited overshoot, peak temperatures occur around the middle of the century (largely due to the inertia of the climate and the fact that society cannot turn off all of its greenhouse gas emitting systems overnight). Over the roughly 25 year period between now and the middle of the century, the additional warming induced by methane emissions is closely correlated with cumulative methane emissions over this period, partly because its half-life of 11.8 years is a significant fraction of the period (i.e. the methane has relatively little time to be broken down in the atmosphere so behaves somewhat like a long-lived greenhouse gas (again, over a period of 25 years)). For longer-lived greenhouse gases like nitrous oxide (N_2O), with a half-life of 109 years (Table 7.15 in IPCC AR6 WG1[36]), the long-lived nature is even starker when considering the next 25 year period. As a result, the linear relationship between warming and cumulative emissions of N_2O and other longer-lived gases is even clearer. The dependence on cumulative emissions becomes yet more pronounced when one considers emission profiles bound by today's emission levels as a starting point and emission reduction rates derived from a set of plausible mitigation actions[37]. For all these reasons, cumulative greenhouse gas emissions are a reasonable indicator[38] of warming impact over the decades between now and mid-century.

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[36] Forster, P., T. Storelvmo, K. Armour, W. Collins, J.-L. Dufresne, D. Frame, D.J. Lunt, T. Mauritsen, M.D. Palmer, M. Watanabe, M. Wild, and H. Zhang, 2021: 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* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 923–1054, doi:10.1017/9781009157896.009.

[37] There is discussion in the literature of more theoretical, abstract emission profiles in which the dependence on cumulative emissions breaks. I do not engage with this literature here because it is not relevant for the discussion.

[38] The relationship between cumulative CO_2 and cumulative GHG comes with an uncertainty of around 100 $GtCO_2$-eq. In warming terms, this is a bit less than 0.1°C (assuming the best-estimate from AR6 for the sensitivity of the climate system to anthropogenic emissions of 0.00165 K per $GtCO_2$). As a result, using this relationship allows me distinguish between emissions consistent with warming of 1.5°C and 2°C, but I would be less confident using it to distinguish between emissions consistent with warming of e.g. 1.5°C and 1.6°C.

Q.4 What were the remaining cumulative greenhouse gas emissions until 2050 as at the following dates, consistent with a CO_2 budget to limit global temperature increase to 1.5°C above pre-industrial levels as of: (a) 2014; and (b) 2022?

Calculating remaining cumulative greenhouse gas emissions until 2050

38. To calculate remaining cumulative greenhouse gas emissions until 2050 consistent with a CO_2 budget to limit global temperature increase to 1.5°C above pre-industrial levels, I begin with the IPCC's latest assessment of the remaining carbon budget. I apply best-estimate default assumptions for all further steps (summarised in Table 1).

39. In its latest assessment report, the IPCC assessed the remaining CO_2 budget to limit warming relative to 1850-1900 to less than 1.5°C with a 50% chance to be 500 $GtCO_2$[39] from the beginning of 2020[40].

40. I first update the budget so that it is for warming relative to pre-industrial, in line with The Paris Agreement (see also Paragraph 21) rather than warming relative to 1850-1900 as reported by the IPCC. The IPCC's best-estimate of the difference between pre-industrial temperatures and 1850-1900 average temperatures was 0.1°C. Considering Table 5.8 of IPCC AR6 WG1[41], a difference in warming of 0.1°C is equivalent to a reduction in the budget of 150 $GtCO_2$. Removing this 150 $GtCO_2$ from the starting budget of 500 $GtCO_2$ gives us a budget applicable to warming relative to pre-industrial of 350 $GtCO_2$.

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[39] The IPCC rounds their reported CO_2 budgets to the nearest 50 $GtCO_2$ to reflect the precision of their estimates. My calculations are performed using a higher precision than this to ensure that rounding errors do not propagate through this analysis and I report the derived results to a greater precision than this to ensure that it is as simple as possible for the reader to follow the analysis. Arguably, the final results could be rounded in line with the precision of the IPCC's initial estimate. I leave this step for the reader to keep the transparency of how the numbers are derived.

[40] Canadell, J.G., P.M.S. Monteiro, M.H. Costa, L. Cotrim da Cunha, P.M. Cox, A.V. Eliseev, S. Henson, M. Ishii, S. Jaccard, C. Koven, A. Lohila, P.K. Patra, S. Piao, J. Rogelj, S. Syampungani, S. Zaehle, and K. Zickfeld, 2021: 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* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 673–816, doi:10.1017/9781009157896.007.

[41] Canadell, J.G., P.M.S. Monteiro, M.H. Costa, L. Cotrim da Cunha, P.M. Cox, A.V. Eliseev, S. Henson, M. Ishii, S. Jaccard, C. Koven, A. Lohila, P.K. Patra, S. Piao, J. Rogelj, S. Syampungani, S. Zaehle, and K. Zickfeld, 2021: 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* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 673–816, doi:10.1017/9781009157896.007.

41. To answer question 4(a), I need to calculate the budget from 2014 (see also Paragraph 18. As a result, I next update the CO_2 budget so it is a budget from the beginning of 2014, not the beginning of 2020, by simply adding the historical emissions over the 2014-2020 period. Those global CO_2 emissions between 2014 and 2020 are estimated to be 245 $GtCO_2$[42,43]. Adding these 245 $GtCO_2$ to the 350 $GtCO_2$ from the previous step, the remaining global CO_2 budget from the start of 2014 is 595 $GtCO_2$.

42. Next, I convert the CO_2 budget into remaining cumulative greenhouse gas emissions (see also Paragraphs 25-37). I do this based on IPCC AR6 Figure 1.29 (see Figure 1 above), which shows the relationship between cumulative CO_2 emissions (i.e. the CO_2 budget) and cumulative greenhouse gas emissions. The IPCC figure (Figure 1 above) shows these relationships for 2013 - 2050 from scenarios used in the IPCC's Special Report on 1.5°C whereas here I need them for 2014 - 2050 and I use the latest set of IPCC scenarios, those from AR6 WG3. The updated version of the IPCC figure is shown in Figure 2 below. Based on this conversion, a remaining global CO_2 budget from the start of 2014 of 595 $GtCO_2$ is consistent with remaining global cumulative greenhouse gas emissions until 2050 of 951 $GtCO_2$-eq.

[42] Friedlingstein, P., O'Sullivan, *et. al*: Global Carbon Budget 2022, Earth Syst. Sci. Data, 14, 4811–4900, https://doi.org/10.5194/essd-14-4811-2022, 2022.
[43] Due to an update to using the latest available data, this is a slightly larger increase than the equivalent used in the 2023 report I co-authored available here (https://www.climate-resource.com/reports/wwf/20230612_WWF-Aus-Targets.pdf).

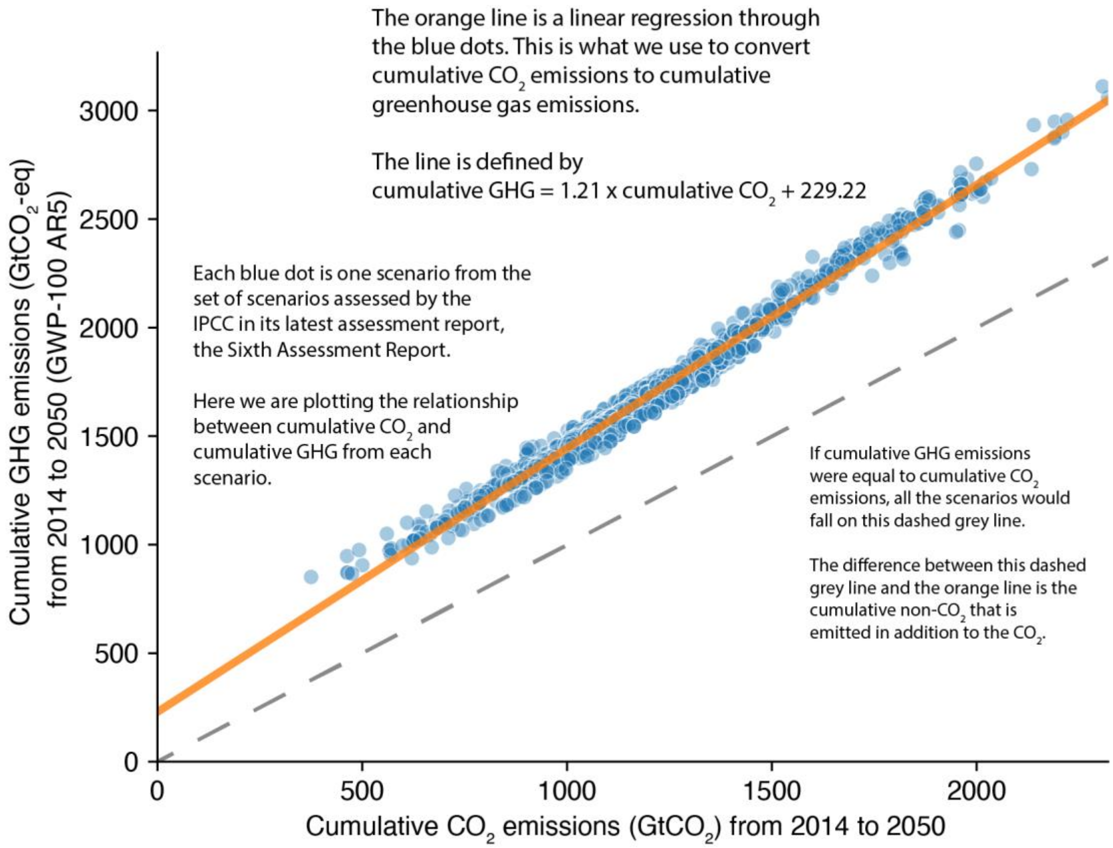

Figure 2 Relationship between cumulative CO_2 emissions and cumulative GHG emissions from 2014 to 2050 based on AR5 GWP-100 in IPCC AR6 WG3 scenarios. This an update of the inset of Figure 1.29 from IPCC AR6 WG1 (reproduced as Figure 1 above) to instead use the conversion between non-CO_2 emissions and CO_2 used in Australia's emissions reporting (specifically the AR5 GWP-100 metric) rather than the conversion used in Figure 1.29 from IPCC AR6 WG1 (specifically the AR4 GWP-100 metric) and to use the set of scenarios assessed in the IPCC's latest assessment report, AR6, rather than the set of scenarios assessed in the IPCC's earlier 2018 Special Report on 1.5°C. The calculations were all performed using Python, with the statsmodels package[44] being used for calculating the linear regression. All code required to reproduce the calculations is available for further inspection as needed.

43. As discussed in Paragraph 23, the emissions accounting conventions used by countries are not the same as those used in the IPCC's assessment of the remaining CO_2 budget, given that the IPCC only accounts for anthropogenic emissions, while countries take credit for some natural carbon uptake in terrestrial plants (a response driven by anthropogenically heightened CO_2 concentrations). To account for this difference, I reduce the CO_2 component of the remaining global cumulative greenhouse gas

[44] Seabold, Skipper, and Josef Perktold. "statsmodels: Econometric and statistical modeling with python." *Proceedings of the 9th Python in Science Conference*. 2010.

emissions conservatively by 15% in line with the scientific literature[45]. In other words, 15% of 595 $GtCO_2$ (the remaining global CO2 budget from the start of 2014), i.e. 89 $GtCO_2$, must be removed to account for the fact that national reporting includes natural carbon uptake. Removing these 89 $GtCO_2$ from the 951 $GtCO_2$-eq from the previous step gives us remaining global cumulative greenhouse gas emissions until 2050 of 862 $GtCO_2$-eq based on accounting conventions consistent with countries' reported emissions to the UNFCCC.

44. As discussed in Paragraph 24, countries only report emissions within their territories and explicitly exclude emissions from international aviation and shipping. As a result, I must exclude future emissions from these sectors in order to arrive at a number which can sensibly be used when sharing emissions between countries. 2014-2050 cumulative emissions from international aviation and shipping can be estimated from, for example, the SSP1-1.9 scenario[46,47,48], which is approximately in line with limiting global temperature increase to 1.5°C above pre-industrial levels. In this scenario, greenhouse gas emissions from international aviation and shipping are 39 $GtCO_2$-eq[49]. Removing these 39 $GtCO_2$-eq from the cumulative greenhouse gas emissions limit of 862 $GtCO_2$-eq from the previous step gives a limit for cumulative greenhouse gas emissions between 2014 and 2050 in line with UNFCCC conventions and excluding international shipping and aviation of 823 $GtCO_2$-eq.

45. As of 2014, the above calculation steps derive that the best-estimate of the remaining global cumulative greenhouse gas emissions until 2050 consistent with a CO_2 budget to limit global temperature increase to 1.5°C above pre-industrial levels were 823 $GtCO_2$-eq.

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[45] See Supplementary Figure 8b of Grassi, G., Stehfest, E., Rogelj, J., van Vuuren, D., Cescatti, A., House, J., Nabuurs, G.-J., Rossi, S., Alkama, R., Viñas, R. A., Calvin, K., Ceccherini, G., Federici, S., Fujimori, S., Gusti, M., Hasegawa, T., Havlik, P., Humpenöder, F., Korosuo, A., . . . Popp, A. (2021). Critical adjustment of land mitigation pathways for assessing countries' climate progress. *Nature Climate Change*, *11*(5), 425-434. https://doi.org/10.1038/s41558-021-01033-6

[46] Riahi, K., Van Vuuren, D.P., Kriegler, E., Edmonds, J., O'neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O. and Lutz, W., 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global environmental change*, *42*, pp.153-168.

[47] Van Vuuren, D.P., Stehfest, E., Gernaat, D.E., Doelman, J.C., Van den Berg, M., Harmsen, M., de Boer, H.S., Bouwman, L.F., Daioglou, V., Edelenbosch, O.Y. and Girod, B., 2017. Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Global Environmental Change*, *42*, pp.237-250.

[48] O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., Van Ruijven, B.J., Van Vuuren, D.P., Birkmann, J., Kok, K. and Levy, M., 2017. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global environmental change*, *42*, pp.169-180.

[49] Using the SSP1-1.9 scenario assumes that international aviation and shipping emissions are at the lowest end of the available quantifications. This is a more conservative assumption (i.e. leaves more room for emissions from within countries' territorial boundaries) than that made in the 2023 report I co-authored available here (https://www.climate-resource.com/reports/wwf/20230612_WWF-Aus-Targets.pdf).

46. Based on the above, I can adjust the starting point to the beginning of 2022 by subtracting total greenhouse gas emissions between 2014 and 2022 of 377 $GtCO_2$-eq.

47. As of the start of 2022, the best-estimate is that the remaining global cumulative greenhouse gas emissions until 2050 consistent with a CO_2 budget to limit global temperature increase to 1.5°C above pre-industrial levels were 446 $GtCO_2$-eq.

Table 1 Summary of steps taken to answer Question 4.

Step	**Relevant paragraph**	**Adjustment**	**Running total**	**Running total brief description**
IPCC remaining budget from start of 2020 for a 50% chance of keeping warming relative to 1850-1900 below 1.5°C	39		500 $GtCO_2$	
Update to make it warming relative to pre-industrial, not 1850-1900	40	-150 $GtCO_2$	350 $GtCO_2$	CO_2 budget for warming to pre-industrial
Adjust to budget from start of 2014	41	+245 $GtCO_2$	595 $GtCO_2$	CO_2 budget from start of 2014
Convert to corresponding limit on cumulative greenhouse gas emissions	42	+356 $GtCO_2$-eq (see text and Figure 2)	951 $GtCO_2$-eq	Cumulative greenhouse gas emissions from start of 2014
Convert to accounting convention used by countries	43	-89 $GtCO_2$-eq (see text)	862 $GtCO_2$-eq	Cumulative greenhouse gas emissions from start of 2014 in line with country reporting
Remove international aviation and shipping emissions	44	-39 $GtCO_2$-eq	823 $GtCO_2$-eq	Remaining cumulative greenhouse gas emissions from 2014 until 2050 consistent with a CO_2 budget to limit global temperature increase to 1.5°C above pre-industrial levels (see Paragraph 45)
Remove global GHG emissions from 2014 to 2022	46	-377 $GtCO_2$-eq	446 $GtCO_2$-eq	Remaining cumulative greenhouse gas emissions from 2022 until 2050 consistent with a CO_2 budget to limit global temperature increase to 1.5°C above pre-industrial levels (see Paragraph 47)

Q.5 If global emissions remained at 2019 levels, what would happen to the CO_2 budget to limit global temperature increase to 1.5°C above pre-industrial levels?

48. The Global Carbon Project estimates that anthropogenic CO_2 emissions in 2019 were 41.7 $GtCO_2$ / yr[50]. As stated above, the global CO_2 budget for a 50% chance of limiting global temperature increase to 1.5°C from the start of 2020 onwards was 500 $GtCO_2$. If global CO_2 emissions were to stay at 2019 levels, the global CO_2 budget for a 50% chance of limiting global temperature increase to 1.5°C would be used up in 12.0 years (which is 500 $GtCO_2$ divided by 41.7 $GtCO_2$ / yr), i.e. by the start of 2032.

National emissions consistent with the global CO_2 Budget

Q.6 Is it possible to determine cumulative national greenhouse gas emissions until 2050 consistent with a CO_2 budget to limit global temperature increase to 1.5°C above pre-industrial levels? If so, how?

Allocating cumulative greenhouse gas emissions to countries

Considerations

49. Once global limits on cumulative greenhouse gas emissions are established, the next question is what the share of those emissions should be for each country. An analogy for this is sharing a rubbish skip with your neighbours. The skip can only take so much rubbish (this is analogous to the limit on cumulative greenhouse gas emissions). If one of the neighbours puts all their rubbish in the skip straight away, there is less room for everyone else. If someone takes more than their fair share of space, then there is less room for everyone else. If everyone takes more than their fair share, then you end up with rubbish on the street, creating a new problem which everyone has to deal with. The key question is how much each neighbour should be allowed to put into the skip and how that allocation should be decided: should the allocation be based on need, how much rubbish each neighbour has already put in the skip, on wealth, on the ability to avoid creating rubbish in the first place or on something else?

50. The international context provides some information on how emissions can be allocated to countries in ways that align with international agreements. The Paris Agreement is an international agreement between all parties to the United Nations Framework Convention on Climate Change (UNFCCC), of which Australia is one. In The Paris Agreement's Article 4.1, countries committed to 'reach global peaking of greenhouse gas emissions as soon as possible, recognizing that peaking will take longer for developing country Parties, and to undertake rapid reductions thereafter in accordance with best

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[50] Friedlingstein, P., O'Sullivan, *et. al*: Global Carbon Budget 2022, Earth Syst. Sci. Data, 14, 4811–4900, https://doi.org/10.5194/essd-14-4811-2022, 2022.

available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century, on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty'[51]. This sets the international context through which emissions allocations relevant to policy questions have been investigated.

51. There is a wide range of literature on allocating emissions to countries, which has emerged as a specialised body of literature to which I have contributed[52,53] (and engaged with as part of those contributions). This literature necessarily combines insights on cumulative emissions consistent with different warming limits from climate science and considerations of equity. Before The Paris Agreement, the IPCC examined a number of different effort-sharing regimes in its Fifth Assessment Report[54]. Since then, many other papers have considered how emissions could be allocated to countries in line with agreed principles. Robiou du Pont *et al.*[55], of which I was a co-author, quantified allocations in line with the key categories considered by the IPCC and a more recent paper quantified emissions allocations starting from principles of international law and The Paris Agreement[56] (for a recent list of research on allocating emissions to countries, see the list maintained by the Climate Action Tracker[57]). There is no consensus on how exactly emissions should be allocated to countries. However, as I will discuss in the coming paragraphs, methodologies fall into a few broad categories and quantifications based on these different methodologies can produce allocations which can differ by an order of magnitude from each other.

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[51] Article 4.1, United Nations (2015). The Paris Agreement. Available at https://unfccc.int/sites/default/files/english_paris_agreement.pdf, last accessed 10 July 2023.

[52] Meinshausen, M., Jeffery, L., Guetschow, J., Robiou du Pont, Y., Rogelj, J., Schaeffer, M., Höhne, N., den Elzen, M., Oberthür, S., & Meinshausen, N. (2015). National post-2020 greenhouse gas targets and diversity-aware leadership. *Nature Climate Change*, *5*(12), 1098-1106. https://doi.org/10.1038/nclimate2826

[53] Robiou du Pont, Y., & Meinshausen, M. (2018). Warming assessment of the bottom-up Paris Agreement emissions pledges. *Nature Communications*, *9*(1), 4810. https://doi.org/10.1038/s41467-018-07223-9

[54] See Section 6.3.6.6 in Clarke L., K. Jiang, K. Akimoto, M. Babiker, G. Blanford, K. Fisher-Vanden, J.-C. Hourcade, V. Krey, E. Kriegler, A. Löschel, D. McCollum, S. Paltsev, S. Rose, P.R. Shukla, M. Tavoni, B.C.C. van der Zwaan, and D.P. van Vuuren, 2014: Assessing Transformation Pathways. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[55] Robiou du Pont, Y., & Meinshausen, M. (2018). Warming assessment of the bottom-up Paris Agreement emissions pledges. *Nature Communications*, *9*(1), 4810. https://doi.org/10.1038/s41467-018-07223-9

[56] Lavanya Rajamani, Louise Jeffery, Niklas Höhne, Frederic Hans, Alyssa Glass, Gaurav Ganti & Andreas Geiges (2021) National 'fair shares' in reducing greenhouse gas emissions within the principled framework of international environmental law, *Climate Policy, 21:8*, 983-1004, DOI: 10.1080/14693062.2021.1970504

[57] See section "Literature used as input" at https://climateactiontracker.org/methodology/cat-rating-methodology/fair-share/, last accessed 10 July 2023

52. In the literature on allocating cumulative greenhouse gas emissions to countries, three key considerations have been dominant: equality, responsibility and capability. In essence, discussions boil down to three ideas: the extent to which every person on Earth should be allowed to emit the same, the extent to which the allocations should take into account past emissions, i.e., responsibility for climate change to date, and the extent to which allocations should take into account the different circumstances of nations on Earth, i.e., the extent to which wealthier nations should lead the action (commonly referred to using the short-hand 'capability', where capability refers to 'capability in terms of capital stock rather than technological capability, governance etc.').

53. The literature on allocating cumulative greenhouse gas emissions to countries can be broken down into three broad categories. At one end, there are approaches based on present-day emissions that allocate greater emissions allocations to those who have high emissions today. These approaches are generally known as 'grandfathering' approaches. In the middle of the spectrum are approaches based on 'equality', i.e. everyone on Earth receives roughly the same emissions allocation, irrespective of present-day emissions, historical responsibility or capability. At the other end of the spectrum, there are approaches based on responsibility and capability that allocate greater allocations to those who have emitted less in the past and who have less ability (often measured in money terms) to pay for the transition to net-zero.

54. In the literature on allocating cumulative greenhouse gas emissions to countries, grandfathering approaches are often criticised as inequitable, given that they provide higher pollution 'allocations' to those who polluted more in the past. Grandfathering does not take into account the key ideas of equity: responsibility and capability. Instead, elements of grandfathering, either in a pure implementation or as part of other allocation approaches, are based on ideas of political feasibility and avoiding economic shocks (i.e. making all transitions smooth). Nonetheless, it is possible to calculate countries' emissions allocations under 'pure' grandfathering approaches and given that some countries' national targets seem to imply this approach, it is implicitly part of and forms one end of the spectrum of opinions voiced in the international debate on the distribution of future mitigation efforts, albeit not necessarily a 'fair' distribution[58,59].

55. It is also possible to calculate countries' emissions allocations based on ideas of equality. Such calculations are relatively simple, as emissions allocations are simply

[58] Robiou du Pont, Y., & Meinshausen, M. (2018). Warming assessment of the bottom-up Paris Agreement emissions pledges. *Nature Communications*, *9*(1), 4810. https://doi.org/10.1038/s41467-018-07223-9
[59] Bretschger, L. (2013). Climate policy and equity principles: fair burden sharing in a dynamic world. *Environment and Development Economics*, *18*(5), 517-536. https://doi.org/10.1017/S1355770X13000284

distributed according to each countries' population. This approach has been performed in many places, with Robiou du Pont *et al.*[60] providing one example.

56. There is a wide range of scholarship on quantifying countries' emissions allocations based on equity principles, typically responsibility and capability. Such quantifications allocate greater emissions allocations to those who have previously emitted less and have less ability to transition their economies. For example, Robiou du Pont *et al.*[61] provide a quantification based on each countries' capability and a widely used report by experts from Brazil, South Africa, India and China (the 'BASIC' countries)[62] provides a quantification based on a reversal of historical emissions.

57. There are examples where countries explicitly refer to the literature on allocating cumulative emissions to countries in setting their own targets. The approach taken by countries varies. Denmark[63] starts with an approach based on equal emissions for all people (i.e. per capita). In a German Federal Constitutional Court decision[64], the court accepted a proposal by the German Advisory Council on the Environment ("Sachverständigenrat für Umweltfragen (SRU)")[65] for an equal per capita allocation. The Danish analysis notes that their share would be even smaller than an equal per capita approach if other ideas of equity were given more weight and that there are good reasons for doing this. In their latest advice[66], the European Scientific Advisory Board on Climate Change (ESABCC) discusses multiple perspectives on fair shares. In their Figure 3, they calculate the EU's share of the remaining budget under different quantifications including equal per capita and capability based on capital stock. Notably,

[60] Robiou du Pont, Y., & Meinshausen, M. (2018). Warming assessment of the bottom-up Paris Agreement emissions pledges. *Nature Communications*, *9*(1), 4810. https://doi.org/10.1038/s41467-018-07223-9

[61] Robiou du Pont, Y., & Meinshausen, M. (2018). Warming assessment of the bottom-up Paris Agreement emissions pledges. *Nature Communications*, *9*(1), 4810. https://doi.org/10.1038/s41467-018-07223-9

[62] BASIC experts (2011). Equitable access to sustainable development: Contribution to the body of scientific knowledge. BASIC expert group: Beijing, Brasilia, Cape Town and Mumbai. Available at https://gdrights.org/wp-content/uploads/2011/12/EASD-final.pdf, last accessed 4 July 2023.

[63] The Danish Council on Climate Change, A framework for Danish climate policy: Input for a new Danish climate act with global perspectives, October 2019, p 9-11. Available at https://eeac.eu/wp-content/uploads/2020/04/English-translation-A-framework-for-Danish-climate-policy.pdf, last accessed 4 July 2023

[64] German High Court decision here: https://www.bundesverfassungsgericht.de/SharedDocs/Entscheidungen/DE/2021/03/rs20210324_1bvr265618.html, last accessed 4 July 2023. See also A. Bauser (2021) German Law Journal, Volume 22, Issue 8 DOI: https://doi.org/10.1017/glj.2021.81

[65] German Advisory Council on the Environment (2020). Using the CO_2 budget to meet the Paris climate targets. Available at https://www.umweltrat.de/SharedDocs/Downloads/EN/01_Environmental_Reports/2020_08_environmental_report_chapter_02.html, last accessed 4 July 2023

[66] European Scientific Advisory Board on Climate Change (2023). Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050. https://climate-advisory-board.europa.eu/reports-and-publications/scientific-advice-for-the-determination-of-an-eu-wide-2040/esabcc_advice_eu_2040_target.pdf/@@display-file/file, last accessed 4 July 2023.

the ESABCC exclude grandfathering and cost-effectiveness because they are not based on common ideas of equity, with grandfathering being identified as particularly problematic because of its maintenance of the status quo in terms of the regional distribution of emissions. As a slightly different method, the UK starts by assessing what is possible if it applies the highest possible ambition, and only considers how such a pathway fits within the global context as a final consistency check[67].

[67] Committee on Climate Change (2020). The Sixth Carbon Budget: The UK's path to Net Zero. https://www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-The-UKs-path-to-Net-Zero.pdf, last accessed 4 July 2023.

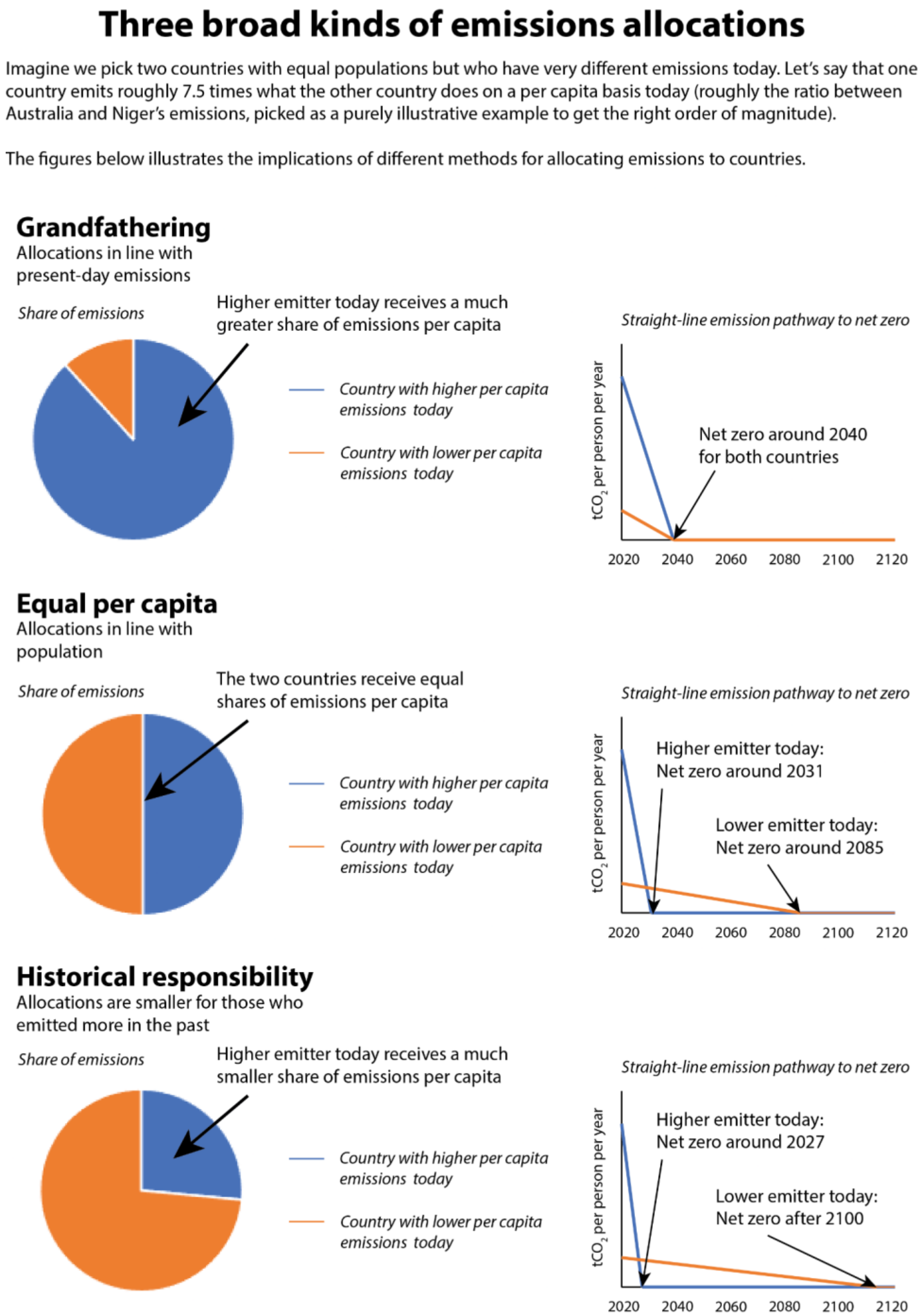

Figure 3 Three broad methods for allocating remaining cumulative emissions to countries. This figure illustrates the broad themes for the methodologies presented in this report, but is not an exact quantification of them. The pathways are illustrative on the basis of countries choosing to follow a straight-line path to net zero. This may not always be the case in the real world, for example a country with a straight-line net zero year of 2100 may instead choose to initially increase its emissions before reaching net zero earlier (e.g. 2080). Such a pathway could have the same cumulative emissions hence climate impact but be more in line with other policies/domestic context.

Australian context

58. The questions that follow focus on Australia, so I will switch to focussing on the Australian context at this point. This has the added benefit of greatly simplifying the number of variables in determining emission allocations for countries and hence complexity of explanation required. In the Australian context, three key allocations provide a reasonable overview of the range of allocations which could be applied to Australia.

Australian context - CCA 2014

59. The first is the allocation used by the Climate Change Authority (CCA) in its 2014 review of Australian Government targets and progress towards meeting those targets. In 2014, the Australian Government's Climate Change Authority (CCA) completed a review of Australia's greenhouse gas emissions reduction goals. The CCA was an independent statutory body established under the Climate Change Authority Act 2011 to provide expert advice to the Australian Government on climate change policy. As part of its review, it explicitly considered global action on emissions mitigation and different methods for sharing the global emissions budget. As Australia's main statutory body for advising the government on emission's targets, its advice was widely discussed and its recommendations continue to be used today in many contexts. As part of the review, I was consulted on global emissions budgets in line with the mitigation targets considered by the CCA, but I did not contribute to calculating Australia's fair share as part of this review nor did I contribute any text to the report.

60. The CCA's allocation is a form of grandfathering that provides an allocation for Australia at the high-end of the range of allocations seen in the literature. In quantitative terms, the CCA allocated 0.97% of remaining global cumulative emissions to Australia.

61. To understand why this methodology is a form of grandfathering, it is necessary to explore it in more detail. In essence, the CCA 2014 allocation is based on an idea described as 'modified contraction and convergence'. The idea is that developed countries with higher per capita emissions today reduce their emissions per capita from today onwards while developing countries are allowed to keep increasing their emissions per capita for a period. As emissions per capita in developed countries fall and emissions per capita in developing countries rise, there will come a point at which they become equal. From this point onwards, the emissions per capita of all nations fall at the same rate towards net zero. In essence, developing countries are allowed to keep emitting until they 'catch up' to emissions of developed countries, at which point all nations must make reductions at the same per capita rate. As a result, developed countries have emissions per capita greater than or equal to those of developing countries at all times, so end up with a larger share of cumulative emissions per capita in the future. Because the methodology gives a greater share of cumulative emissions per capita in the future to countries with higher emissions per capita today, it is a form of grandfathering.

62. As stated above, the CCA 2014 method allocates 0.97% of the world's cumulative greenhouse gas emissions[68] for 2013-2050 to Australia. I will use this number to explore the implications for Australia under an emissions allocation that gives Australia a share at the high-end of the range seen in the literature. I have assumed that the calculation would give a very similar share had it been calculated for Australia's share of cumulative greenhouse gas emissions from 2014-2050, rather than from 2013-2050, as the time frames are nearly identical.

Australian context - equal per capita

63. The second interpretation of equity which is relevant is very simple: every person on Earth receives the same share of remaining cumulative greenhouse gas emissions. Put in practice, this means that cumulative emissions are shared based on each nation's share of the global population.

64. For Australia, this gives a share of 0.33% (based both on 2014 and present-day numbers)[69]. This share sits in the middle of the range of allocations for Australia proposed in the literature.

Australian context - higher weighting on historical responsibility and capability

65. In some of the equity literature [70,71], a greater weight is placed on historical responsibility and capability than equality. Under these allocation methods, countries which have large historical emissions, like Australia, receive a smaller share of cumulative emissions and countries which have high capability (typically measured via GDP per capita), again like Australia, also receive a smaller share of cumulative emissions. The rationale for the first reduction is that countries with high historical emissions should get less in future to account for the fact that they have already used up some of their all-time share. The rationale for the second reduction is that countries with higher capability should take the lead and make room for countries with less capital with which to transition their economies.

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[68] Again, this is the cumulative greenhouse gas emissions to be shared amongst countries i.e. emissions from international shipping and aviation must be removed from the global cumulative greenhouse gas emissions limit before applying this share.

[69] UN Department of Economic and Social Affairs, Population Division. World Population Prospects 2022. https://population.un.org/wpp/, last accessed 4 July 2023.

[70] Robiou du Pont, Y., & Meinshausen, M. (2018). Warming assessment of the bottom-up Paris Agreement emissions pledges. *Nature Communications*, *9*(1), 4810. https://doi.org/10.1038/s41467-018-07223-9

[71] BASIC experts (2011). Equitable access to sustainable development: Contribution to the body of scientific knowledge. BASIC expert group: Beijing, Brasilia, Cape Town and Mumbai. Available at https://gdrights.org/wp-content/uploads/2011/12/EASD-final.pdf, last accessed 4 July 2023.

66. Under this interpretation, Australia receives a share which is significantly less than its per capita share because of its high historical emissions and high capability (again, measured in terms of capital stock). I don't quantify this share precisely here because, as will be shown in the following section, even under an equal-per-capita approach Australia has already exhausted its share of remaining cumulative emissions and an equal-per-capita approach is more lenient towards Australia than historical responsibility or capability approaches.

Q.7 What were the remaining cumulative national greenhouse gas emissions for Australia until 2050 as at the following dates, consistent with a CO_2 budget to limit global temperature increase to 1.5°C above pre-industrial levels as of: (a) 2014; and (b) 2022?

Calculations

67. In this section, I calculate cumulative greenhouse gas emissions for Australia in line with 1.5℃ under the three different allocation methods presented above. In all cases, I begin with the remaining global cumulative greenhouse gas emissions until 2050 consistent with a CO_2 budget to limit global temperature increase to 1.5°C above pre-industrial levels as at 2014 of 823 $GtCO_2$-eq. The reason why I keep the 2014 starting date as in earlier deliberations of Australia's fair share (CCA, 2014) is that under a budget-informed approach, it is important to keep track of whether early years featured higher or lower emissions. Always updating the starting year to the latest current year would negate one of the key features of cumulative carbon emission approaches, namely that early reductions allow more emissions later on and higher earlier emissions require steeper reductions later on.

68. To calculate remaining cumulative national greenhouse gas emissions for Australia until 2050 consistent with limiting global temperature increase to 1.5°C as at 2014, I multiply the remaining global cumulative greenhouse gas emissions until 2050 consistent with limiting global temperature increase to 1.5°C by the relevant Australian share. This results in remaining cumulative national greenhouse gas emissions for Australia until 2050 consistent with limiting global temperature increase to 1.5°C as at 2014 of:

    a. 7.98 $GtCO_2$-eq based on an Australian share of 0.97% following CCA (2014).

    b. 2.72 $GtCO_2$-eq based on an Australian share of 0.33% following equal per capita.

    c. less than 2.72 $GtCO_2$-eq based on an Australian share of less than 0.33% following a methodology that puts greater weight on historical responsibility and capability than the equal per capita approach (point b).

69. Straight-line pathways to net zero in line with the above limits would be consistent with the following milestones (Figure 4):

a. for the CCA 2014 0.97% share assuming action started in 2014: emissions reductions below 2005 levels of 47% by 2025, 62% by 2030, 78% by 2035, 93% by 2040 and net zero by 2043.

b. for the equal per capita 0.33% share assuming action started in 2014: net zero by 2024.

c. for the historical responsibility share of less than 0.33% share assuming action started in 2014: net zero before 2024.

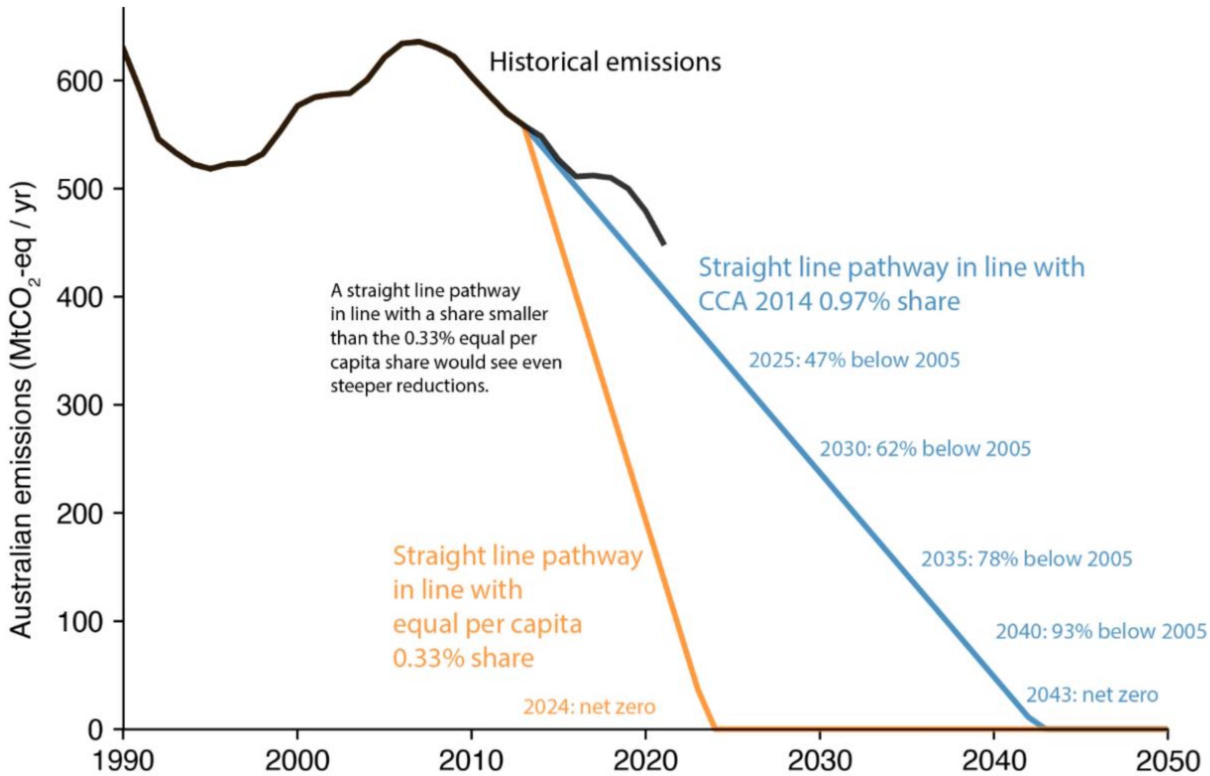

Figure 4 Straight-line pathways to net zero in line with the remaining cumulative emissions limits calculated in response to Q.7(a). These pathways assume that action started in 2014.

70. To calculate remaining cumulative national greenhouse gas emissions for Australia until 2050 consistent with limiting global temperature increase to 1.5°C as at 2022, I subtract Australia's greenhouse gas emissions between the start of 2014 and the start of 2022 of 4.04 $GtCO_2$-eq[72]. This results in remaining cumulative national greenhouse gas emissions for Australia until 2050 consistent with limiting global temperature increase to 1.5°C as at 2022 of:

[72] https://www.dcceew.gov.au/sites/default/files/documents/ageis-state-territory-inventories-2021-emission-data-tables.xlsx, last accessed 4 July 2023. See also https://www.dcceew.gov.au/climate-change/publications/national-greenhouse-accounts-2021/state-and-territory-greenhouse-gas-inventories-2021-emissions, last accessed 4 July 2023.

a. 3.94 $GtCO_2$-eq based on an Australian share of 0.97% following CCA (2014).

b. negative 1.32 $GtCO_2$-eq based on an Australian share of 0.33% following equal per capita i.e. Australia has already exhausted its fair share based on this methodology.

c. less than negative 1.32 $GtCO_2$-eq based on an Australian share of less than 0.33%, i.e. following a methodology that puts greater weight on historical responsibility and capability than plan equal per capita. Under such a methodology, Australia has already exhausted its fair share as at the beginning of 2022.

71. Straight-line pathways to net zero in line with the above limits would be consistent with the following milestones (Figure 5):

a. for the CCA 2014 0.97% share assuming action started in 2022: emissions reductions below 2005 levels of 44% by 2025, 63% by 2030, 83% by 2035 and net zero by 2040.

b. for the equal per capita 0.33% share assuming action started in 2022 no pathway is provided as remaining cumulative greenhouse gas emissions for Australia are already negative.

c. for the historical responsibility share of less than 0.33% share assuming action started in 2022 no pathway is provided as remaining cumulative greenhouse gas emissions for Australia are already negative.

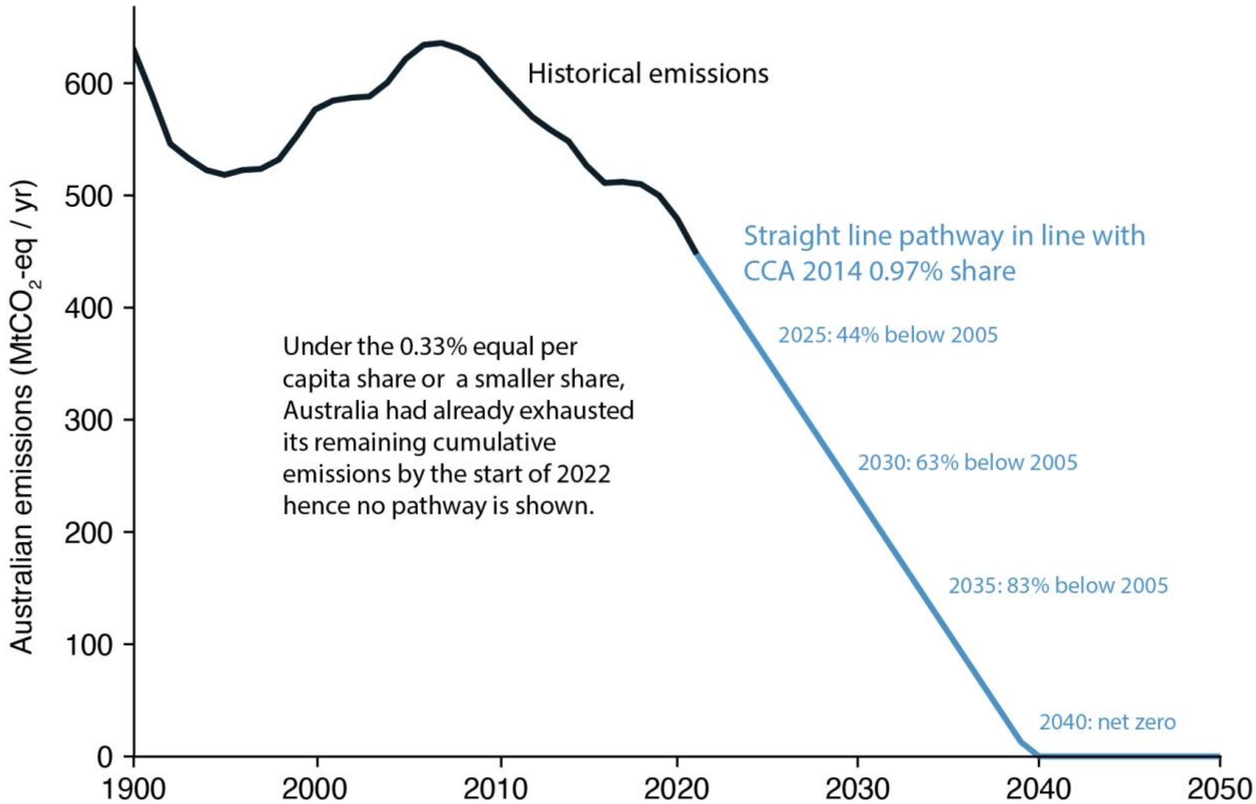

Figure 5 Straight-line pathways to net zero in line with the remaining cumulative emissions limits calculated in response to Q.7(b). These pathways assume that action started in 2022.

Australian emissions reduction targets relative to the global CO_2 Budget

72. To calculate cumulative greenhouse gas emissions associated with Australia's targets, I assume that Australia's emissions would follow a straight-line between the starting year in each question (either 2014 or 2022) and the year in which the target was set (2030 in the questions below). This assumption is a middle of the road assumption which neither assumes strong, early action that would allow a longer tail of emissions for the same cumulative emissions or a delayed action scenario, which would necessitate a steep cliff of emission reductions in order to stay within the same budget. Such near-linear emission reduction pathways have precedent also in other jurisdictions, either implicitly or explicitly[73].

Q.8 As of 2014, was Australia's target of reducing its greenhouse gas emissions by 26-28% of its 2005 levels by 2030 consistent with Australia remaining within the figure(s)

[73] See e.g. Figure 1 of the United States of America Long-term Low Emission Development Strategy, which is close to a linear transition between recent historical and 2050 net-zero emissions. The LT-LEDS strategy is available here: https://unfccc.int/sites/default/files/resource/US-LongTermStrategy-2021.pdf

you identified in Q.7(a) (being the remaining cumulative national greenhouse gas emissions for Australia until 2050 consistent with a CO_2 budget to limit global temperature increase to 1.5°C above pre-industrial levels)?

73. Assuming a straight-line trajectory, the more ambitious interpretation of Australia's 2014 target, i.e. reducing its greenhouse gas emissions by 28% of its 2005 levels by 2030, would lead to cumulative greenhouse gas emissions of 8.50 $GtCO_2$-eq between 2014 and 2030[74].

    a. In Q.7(a), I calculated, assuming Australia's share of global cumulative greenhouse gas emissions is 0.97%, that remaining cumulative national greenhouse gas emissions for Australia between 2014 and 2050 consistent with a CO_2 budget to limit global temperature increase to 1.5°C above pre-industrial levels were 7.98 $GtCO_2$-eq. Under this assumption, by 2030, the target would have seen Australia exhaust its cumulative greenhouse gas emissions limit, even without considering how much would be emitted after 2030. Based on these calculations, as of 2014, Australia's target of reducing its greenhouse gas emissions by 26-28% of its 2005 levels by 2030 was not consistent with remaining within its cumulative greenhouse gas emissions limit.

    b. Also in Q.7(a) I calculated, assuming Australia's share of global cumulative greenhouse gas emissions is 0.33% in line with its per capita share, that remaining cumulative national greenhouse gas emissions for Australia between 2014 and 2050 consistent with a CO_2 budget to limit global temperature increase to 1.5°C above pre-industrial levels were 2.72 $GtCO_2$-eq. Under this assumption, by 2030, the target would have seen Australia emit roughly three times more than its cumulative greenhouse gas emissions limit, even without considering how much would be emitted after 2030. Based on these calculations, as of 2014, Australia's target of reducing its greenhouse gas emissions by 26-28% of its 2005 levels by 2030 was not consistent with remaining within its cumulative greenhouse gas emissions limit.

    c. Also, in Q.7(a) I calculated, assuming Australia's share of global cumulative greenhouse gas emissions is less than 0.33%, i.e. less than its per capita share based on ideas of historical responsibility and capability (measured in terms of capital stock), that remaining cumulative national greenhouse gas emissions for Australia between 2014 and 2050 consistent with a CO_2 budget to limit global temperature increase to 1.5°C above pre-industrial levels were less than 2.72 $GtCO_2$-eq. Under this assumption, by 2030, the target would have seen Australia emit more than three times its cumulative greenhouse gas emissions limit, even without considering how much would be emitted after 2030. Based on these calculations, as of 2014, Australia's target of reducing its greenhouse gas

[74] This was calculated using the Python programming language. The code underpinning these calculations is available for further analysis as needed.

emissions by 26-28% of its 2005 levels by 2030 was not consistent with remaining within its cumulative greenhouse gas emissions limit.

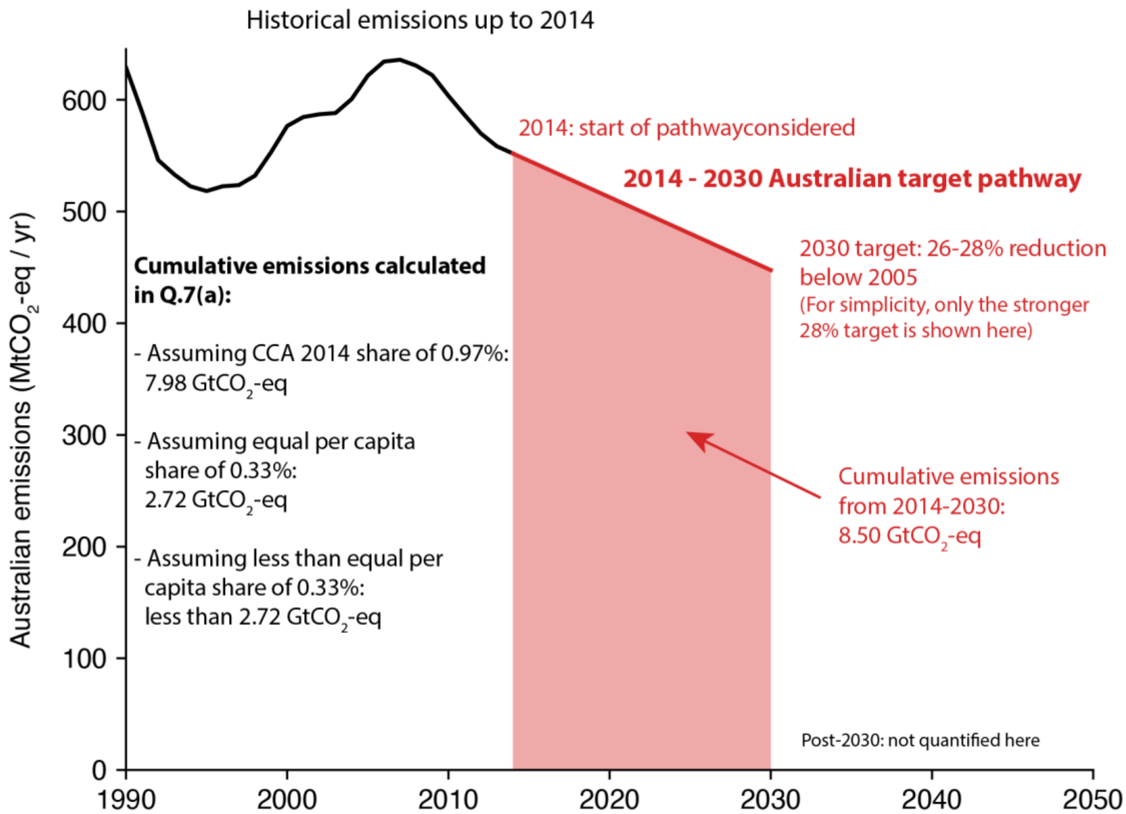

Figure 6 Cumulative emissions under Australia's target as of 2014: reducing greenhouse gas emissions by 26-28% compared to 2005 levels (for simplicity, here I only show the reduction for the upper end of the range i.e. 28% compared to 2005 levels). These are compared to the cumulative emissions calculated in Q.7(a) and can also be compared to straight-line pathways in line with these cumulative emissions limits (Figure 4).

Q.9 As of 2022, was Australia's target of reducing its greenhouse gas emissions by 43% of its 2005 levels by 2030 consistent with Australia remaining within the figure(s) you identified in Q.7(b) (being the remaining cumulative national greenhouse gas emissions for Australia until 2050 consistent with a CO_2 budget to limit global temperature increase to 1.5°C above pre-industrial levels)?

74. Assuming a straight-line trajectory, Australia's 2022 target of reducing its greenhouse gas emissions by 43% of its 2005 levels by 2030 would lead to cumulative greenhouse gas emissions of 3.57 $GtCO_2$-eq between 2022 and 2030.

    a. In Q.7(b), I calculated, assuming Australia's share of global cumulative greenhouse gas emissions is 0.97%, that remaining cumulative national greenhouse gas emissions for Australia between 2022 and 2050 consistent with a CO_2 budget to limit global temperature increase to 1.5°C above pre-industrial levels were 3.94 $GtCO_2$-eq. Under this assumption, by 2030, the target would leave Australia with 0.37 $GtCO_2$-eq to emit after 2030. According to the current targets, Australia's emissions will be 0.35 $GtCO_2$-eq / yr in 2030 so Australia would have roughly one year to reach net zero (if it emitted the same in 2031 as in 2030 before being net zero from 2032 onwards) or roughly 2 years to reach net zero (assuming it reduced at a rate of 33% per year after 2030 i.e. emitted two-thirds of 2030 levels in 2031 and one-third of 2030 levels in 2032 before being net zero from 2033 onwards). Based on these calculations, as of 2022, Australia's target of reducing its greenhouse gas emissions by 43% of its 2005 levels by 2030 was consistent with remaining within its cumulative greenhouse gas emissions limit assuming that cumulative emissions after 2030 are only 0.37 $GtCO_2$-eq (roughly equivalent to reaching net zero by the start of 2033).

b. Also in Q.7(b) I calculated, assuming Australia's share of global cumulative greenhouse gas emissions is 0.33% in line with its per capita share, that remaining cumulative national greenhouse gas emissions for Australia between 2022 and 2050 consistent with a CO2 budget to limit global temperature increase to 1.5°C above pre-industrial levels were negative 1.32 $GtCO_2$-eq. Under this assumption, Australia had already exhausted its fair share of cumulative greenhouse gas emissions by the start of 2022. Based on these calculations, as of 2022, Australia's target of reducing its greenhouse gas emissions by 43% of its 2005 levels by 2030 was not consistent with remaining within its cumulative greenhouse gas emissions limit.

c. Also in Q.7(c) I calculated, assuming Australia's share of global cumulative greenhouse gas emissions is less than 0.33%, i.e. less than its per capita share based on ideas of historical responsibility and capability (measured in terms of capital stock), that remaining cumulative national greenhouse gas emissions for Australia between 2022 and 2050 consistent with a CO_2 budget to limit global temperature increase to 1.5°C above pre-industrial levels were less than negative 1.32 $GtCO_2$-eq. Under this assumption, Australia had already exhausted its fair share of cumulative greenhouse gas emissions by the start of 2022. Based on these calculations, as of 2022, Australia's target of reducing its greenhouse gas emissions by 43% of its 2005 levels by 2030 was not consistent with remaining within its cumulative greenhouse gas emissions limit.

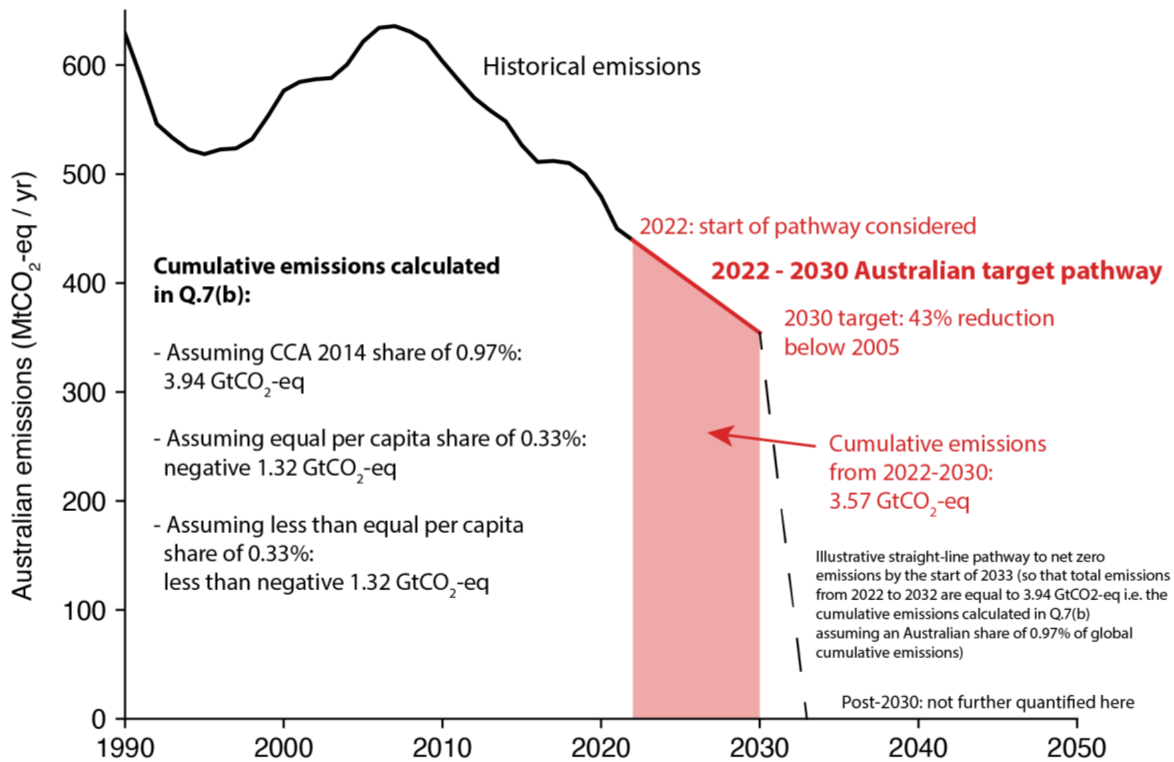

Figure 7 Cumulative emissions under Australia's target as of 2022: reducing greenhouse gas emissions by 43% compared to 2005 levels. These are compared to the cumulative emissions calculated in Q.7(b) and can also be compared to straight-line pathways in line with these cumulative emissions limits (Figure 5). For illustration, we show a straight-line pathway to net zero emissions by the start of 2033, starting from the 2030 target of a 43% reduction below 2005 levels by 2030.

ANNEXURE A

PHI x FINNEY x MCDONALD

31 May 2023

PRIVILEGED AND CONFIDENTIAL

Professor Malte Meinshausen

By email: [redacted]

Dear Professor Meinshausen,

Pabai & Anor v Commonwealth of Australia (VID622/2021) (Proceeding)

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1. Letter of Instruction

1.1. We refer to our letter of retainer dated 27 May 2022 (**Retainer Letter**) and confirm that you are retained by Uncle Pabai Pabai and Uncle Paul Kabai (**Applicants**) to act as an independent expert in the matter of *Pabai & Anor v Commonwealth of Australia*, VID622/2021 (**Climate Class Action**).

1.2. We confirm that the confidentiality obligations in respect of documents and information provided to you for the purpose of this engagement are governed by the terms of the Retainer Letter and Deed of Confidentiality dated 27 May 2022.

1.3. We also remind you of the roles and duties of expert witnesses as set out in the Retainer Letter and ask that you refer to them as you prepare your expert report(s) in this proceeding. In particular, please take some time to reacquaint yourself with the following documents, which we provided to you with our original letter:

(a) the Federal Court of Australia Expert Evidence Practice Note (**GPN-EXPT**), including the Harmonised Expert Witness Code of Conduct (the **Code**) at Annexure A of that Practice Note and the Concurrent Expert Evidence Guidelines (the **Guidelines**) at Annexure B (collectively, the **Practice Note**); and

(b) Rule 23.13 of the *Federal Court Rules 2011* (Cth).

1.4. The purpose of this letter is to request that you prepare a written report, providing your independent expert opinion, in response to the questions set out in Annexure B to this letter.

1.5. Should you in your report make any assumptions in the course of providing your answers**,** please state what those additional assumptions are.

1.6. In order to ensure your report is clearly set out, we ask that you please:

a) provide a brief summary at the beginning of the report;

b) use numbered paragraphs, page numbers and headings where appropriate;

c) provide citations to documents where appropriate; and

d) provide citations to any literature or other materials referred to or relied upon by you in support of your opinions, and a bibliography if necessary.

1.7. Please annex to your report:

a) a detailed curriculum vitae, setting out the training, study and experience that establishes your expertise in relation to the issues raised by these instructions; and

b) this Letter of Instruction.

1.8. At the end of your report, please sign the report and include a declaration to the following effect:

I have read the Federal Court's Expert Evidence Practice Note (GPN-EXPT) and the Harmonised Expert Witness Code of Conduct. I agree to be bound by them and I have complied with them in preparing this Report.

I have made all the inquiries that I believe are desirable and appropriate and that no matters of significance that I regard as relevant have, to my knowledge, been withheld from the Court.

2. Materials

2.1. Set out at Annexure A is an index of the documents provided to you.

2.2. The pleadings have been provided to you so that you are aware of the allegations made and positions taken by each party. Unless an allegation is admitted, the facts are in dispute.

2.3. If you consider that you require any additional information or materials in order to complete your work, please contact us and we will endeavour to provide that additional information and materials.

3. Your Opinion

3.1. We request that you provide a written report addressing the questions set out in Annexure B to this letter.

3.2. In answering the Annexure B questions, please provide detailed reasons for your opinions, including the facts or assumptions that affect your reasoning and conclusions, with specific reference to any material on which you rely in reaching your conclusions.

4. Preparation of Your Report

4.1. We would be grateful if you would set out the answers to the questions at Annexure B in a written report, having regard to the requirements set out in the Federal Court of Australia Expert Evidence Practice Note.

4.2. After you have had the opportunity to consider the questions at Annexure B, we would be grateful if you could advise of any information or material not currently provided to you which you require to respond to any of the Annexure B questions.

4.3. You are requested to complete your report by 14 July 2023.

If you have any questions or if you require any clarification of the facts, assumptions or questions set out in this letter and its annexures, please do not hesitate to contact me [redacted]

Yours faithfully,

Brett Spiegel
Principal Lawyer
Phi Finney McDonald

Encl.

ANNEXURE A

INDEX OF MATERIALS

Tab No.	Date	Description of document(s)
A	**PLEADINGS**	
A1.	15 May 2023	Applicants' Amended Concise Statement
A2.	29 May 2022	Respondent's Amended Concise Statement
A3.	7 October 2022	Amended Originating Application
A4.	11 April 2023	Second Further Amended Statement of Claim
A5.	9 May 2023	Defence to Second Further Amended Statement of Claim

ANNEXURE B

Questions

In your report, please answer the following questions and explain your reasons for your answers. Please address whatever matters are necessary or useful for you to answer the questions to your satisfaction.

Basis of expertise

Q.1 Please describe your academic qualifications and professional background and any other training, study or experience that is relevant to your answering the questions in this Annexure. You may wish to do so by reference to a current curriculum vitae.

The global CO_2 Budget

Q.2 Please explain what a CO_2 Budget is.

Q.3 How do cumulative greenhouse gas emissions relate to international efforts to limit global temperature increase? Please explain how cumulative greenhouse gas emissions are relevant in the context of a CO_2 budget.

Q.4 What were the remaining cumulative greenhouse gas emissions until 2050 as at the following dates, consistent with a CO_2 budget to limit global temperature increase to 1.5°C above pre-industrial levels as of:

(a) 2014; and

(b) 2022?

Q.5 If global emissions remained at 2019 levels, what would happen to the CO_2 budget to limit global temperature increase to 1.5°C above pre-industrial levels?

National emissions consistent with the global CO_2 Budget

Q.6 Is it possible to determine cumulative national greenhouse gas emissions until 2050 consistent with a CO_2 budget to limit global temperature increase to 1.5°C above pre-industrial levels? If so, how?

Q.7 What were the remaining cumulative national greenhouse gas emissions for Australia until 2050 as at the following dates, consistent with a CO_2 budget to limit global temperature increase to 1.5°C above pre-industrial levels as of:

(a) 2014; and

(b) 2022?

Australian emissions reduction targets relative to the global CO_2 Budget

Q.8 As of 2014, was Australia's target of reducing its greenhouse gas emissions by 26-28% of its 2005 levels by 2030 consistent with Australia remaining within the figure(s) you identified in

Q.7(a) (being the remaining cumulative national greenhouse gas emissions for Australia until 2050 consistent with a CO_2 budget to limit global temperature increase to 1.5°C above pre-industrial levels)?

Q.9 As of 2022, was Australia's target of reducing its greenhouse gas emissions by 43% of its 2005 levels by 2030 consistent with Australia remaining within the figure(s) you identified in Q.7(b) (being the remaining cumulative national greenhouse gas emissions for Australia until 2050 consistent with a CO_2 budget to limit global temperature increase to 1.5°C above pre-industrial levels)?

ANNEXURE B

CV Prof. Malte Meinshausen[1]

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& Climate & Energy College
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School of Geography, Earth and Atmospheric Sciences, McCoy Building
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Education & Research

- From Jan 2023 onwards: Professor at the School of Geography, Earth and Atmospheric Sciences, The University of Melbourne
- May 2020 to April 2023: Core Writing Team member of the Synthesis Report to the IPCC Sixth Assessment Cycle
- Apr 2018 to August 2021: Lead Author Intergovernmental Panel on Climate Change AR6 Working Group I
- Jan 2019 – March 2020: Deputy Convener of the Climate & Energy College, The University of Melbourne.
- June 2017- Jan 2019: Co-Director of Energy Transition Hub, The University of Melbourne.
- Feb 2014 – Dec 2022: Associate Professor and ARC Future Fellow at the University of Melbourne, School of Earth Sciences.
- 2013 to 2018: Founding Director of the Australian-German Climate & Energy College (www.climatecollege.unimelb.edu.au) at the University of Melbourne, launched in October 2013 under the auspices of the then current Australian Ambassador to Germany.
- 2008-2011: Team Leader of the PRIMAP group at Potsdam Institute for Climate Impact Research.
- Since May 2006: Researcher at Potsdam Institute for Climate Impact Research, Potsdam, Germany.
- Sep 2005 – Apr 2006: Post-Doc, Guest researcher at the National Centre for Atmospheric Research, NCAR, Boulder, USA, Collaboration with Tom Wigley and Reto Knutti.
- 2002 – 2003: Doctoral courses in macroeconomics, microeconomics and econometrics at the Study Centre Gerzensee, Swiss National Bank
- Oct 2002 – Aug 2005: PhD study in the area "International climate policy and economics", Department of Environmental Sciences, ETH, Supervisor: Prof. Dieter Imboden.
- 1995 – 1999 & 2000 – 2001: Diploma course "Environmental Sciences" at the ETH Zurich. Scholarship by Studientiftung des dt. Volkes. Diploma thesis *(with distinction)* on "Long-term stratospheric chlorine loading prediction" at the Institute for Atmospheric and Climate Science, ETH Zurich, Supervisor: Prof. Thomas Peter
- 1999 – 2000: MSc Environmental Change & Management, University of Oxford, UK. MSc Thesis on "The climatic effect of temporary carbon storage under the Clean Development mechanism of the Kyoto Protocol" *(MSc with distinction)*

Professional experience

- 2020 to current: Co-Director of a new start-up ‘Climate Resource’.
- 2005 to 2015: Scientific & Technical Advisor for German Ministry of Environment on international climate policy. Member of the German delegations to IPCC meetings and UNFCCC negotiations.

[1] Note that my given names as per my passport are ALEXANDER MALTE, while MALTE is my calling name and also my scientific publishing name.

- 2007-2009: Founding Co-Director of the non-for-profit research institute / think tank Climate Analytics (climateanalytics.org), Berlin.
- 2000-2005: Freelance consultancy for government bodies and environmental NGOs on climate policy issues

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IPCC Writing output

- **Lead Author to IPCC Sixth Assessment Report,** *Working Group I, TS and Chapter 1, and contributing author to WG1 Chapter 5, 7, as well as drafting author to Working Group I and III SPMs.*

- ***Core Writing Team Member to IPCC Synthesis Report Sixth Assessment Report.***
- **Contributing Author to IPCC Fourth Assessment Report**, *Working Group I, Chapter 10 & 8, Working Group II, Chapter 2*
- **Contributing Author to IPCC Fifth Assessment Report**, *Working Group I, Chapter 1, 12 & Annex II* (Climate System Scenario Tables)

Book chapters

Teske, S., Pregger, T., Simon, S., Naegler, T., Pagenkopf, J., van den Adel, B., **Meinshausen**, M., Dooley, K., Briggs, C., Dominish, E., Giurco, D., Florin, N., Morris, T., and Nagrath, K.: Methodology, Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-Energy Ghg Pathways for +1.5(Degree)C and +2(Degree)C, edited by: Teske, S., 25-78 pp., 2019.

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Diploma Thesis

Meinshausen, M. (2001). Long term chlorine loading prediction: SiMCeL. Institute for Atmosphere and Climate, IACETH. Zurich, ETH Zurich: 91.http://e-collection.ethbib.ethz.ch/show?type=dipl&nr=22

ANNEXURE C

Zebedee Nicholls

[redacted]

Research Interests

- Reduced complexity climate models
- Integrated assessment modelling and emissions pathways towards net zero
- Cost of climate change and emissions reductions

Employment summary

2021 - **Part-time (50%) position - Research Scholar, International Institute for Applied Systems Analysis**

- Development of carbon and methane cycle of probabilistic emissions-driven emulator (MAGICC) as part of ESM2025 Project
- Assessment of emissions scenarios as part of IPCC, IIASA emissions database and other activities

2021 - **Part-time (25%) position - Research Fellow Emissions Pathway, Australian-German Climate and Energy College, University of Melbourne**

- Compilation of emissions pathway data (collation, harmonisation and infilling) and climate assessment of the resulting emissions pathway(s)

2020 - **Co-Founder and Modelling and Data Director, Climate Resource**

- Head of modelling and data decisions for private climate data provision company

2020 **Casual Research Assistant, Australian-German Climate and Energy College, University of Melbourne**

- Provided input for a website describing the science of global-mean temperature projections, see magicc.autonomycapital.com

2019 - 2020 **Casual Research Assistant, Australian-German Climate and Energy College, University of Melbourne**

- Prepared probabilistic emulator distributions for the IPCC's Sixth Assessment Report

2017 - 2018 **Casual Research Assistant, Australian-German Climate and Energy College, University of Melbourne**

- Worked as part of the CMIP6 ScenarioMIP experiment team to produce projections of future atmospheric GHG concentrations; in particular, supplemented Integrated Assessment Model output to provide a set of emissions with which to drive the reduced complexity climate model MAGICC

Oct-Nov 2016 **Casual Research Assistant, Australian-German Climate and Energy College, University of Melbourne**

- Independently produced plots examining the effect of using different concentration time series on the output of global earth system models

Jul–Sep 2015 **Casual Research Assistant, Environmental Change Institute, University of Oxford**

- Developed a simple Integrated Assessment Model to be used as a teaching and research tool
- Compared the carbon cycle module performance with model output from the CMIP5 experiment

2012 - 2014 **Student ambassador, St. John's College, University of Oxford**

- Represented the college at open days and led tours for prospective students
- Supervised and supported candidates during 2012 admissions interviews

Feb-Aug 2013 **Front of house, Kantina Kartel, Melbourne**

- Co-ordinated front of house and barista team

Apr-Sep 2011 **Father Bob Maguire Foundation Hope Mobile, South Melbourne (volunteer)**

- Worked with other volunteers to provide food and drink service in a volatile environment

Education

2016 - 2021 **Doctor of Philosophy – Science, Australian German Climate Energy College, School of Earth Sciences, University of Melbourne**

- 'On the state of reduced-complexity climate modelling', co-supervised by Associate Professor Malte Meinshausen, Professor David Karoly, Professor Peter Rayner and Dr Alexander Nauels

2012 - 2016 **Master of Physics, University of Oxford, St. John's College**

- First Class Honours, ranked 7th in the cohort
- Masters project: 'Exploring interactions between climate change and economics with idealised integrated assessment models', supervised by Professor Myles Allen

Co-curricular

- Full Blue – Lawn tennis 2013, 2014, 2015, 2016
- Neptune-Atalantas Oxford University Sport teammate of the year 2014 – 15
- Cuppers (intercollegiate competition) tennis winning team member 2016
- Oxford University Lawn Tennis Club Champion 2014, 2016
- Winner Oxford – Cambridge Varsity Athletics Match Seconds Triple Jump 2013

1998 - 2011 **Wesley College, Melbourne**

- International Baccalaureate, score of 44 points: maximum score of 7 in all subjects (Maths, Physics, Chemistry Higher Level, English, Geography, French), 2 out of 3 bonus points (Physics Extended Essay)

Co-curricular

- Debating Association of Victoria Swannie Award - highest scoring Year 12 speaker
- Firsts Tennis APS premiership team 2006
- Honour colours – Tennis, Athletics, Australian Rules Football, Debating, Music

Academic awards

2016	Australian Postgraduate Award, University of Melbourne
2016	Johnson Memorial Prize for MPhys project in Atmospheric, Oceanic and Planetary Physics, University of Oxford
2013	Holmes scholarship for Distinction in first year Physics exams, St.John's College, University of Oxford
2011	Alexander Wawn Scholarship: best Year 12 academic/sporting achievements, Wesley College
2010	Kwong Lee Dow Young Scholar, University of Melbourne
2010	Draper Scholarship: best academic results in Year 11 IB diploma, Wesley College
2006 - 2011	Wesley College Academic Scholarship for Years 7-12

Teaching Experience

2018 - **Co-Course Coordinator, Climate Modelling and Climate Change, University of Melbourne**

- 12 week Masters-level course delivered alongside A/Prof Malte Meinshausen focussing on the development and use of models for climate projections

2018 - **Guest Lecture, Climate Science for Decision Makers, University of Melbourne**

- Delivered a two hour lecture on scenarios and climate projections for Masters students

Feb-Aug 2013 **Private tutor, self-employed, Melbourne**

- Helped 10-18 year old students with Maths, Physics, Chemistry, English, Geography and study techniques

Oct 2015 **Oxford University Doctoral Training Partnership training days**

- Ran a workshop on a simple climate model for first year PhD students alongside Professor Myles Allen, other professors and post-doctoral researchers

Jan-Mar 2014 **Physics in Schools teaching subject, University of Oxford**

- Assisted in local secondary school Physics classes weekly
- Studied the common difficulties that teachers of Science, especially Physics, face in the classroom

Leadership Experience

August 2016 **Prentice Cup Captain**

- Led a team of six Oxford and Cambridge university tennis players on a five and a half week tour of the USA
- Responsible for all team income, expenditure and maintaining good relations with our hosts

2014 - 2016 **Oxford University Lawn Tennis Club Junior President**

- Oversaw the day to day running of the club, both on and off court
- Initiated club sponsorship, facilities and alumni projects and restructured the club's governing bodies

2014 - 2016 **Oxford University Lawn Tennis Club Junior Webmaster**

- Learnt basic html and css coding skills to takeover from the previous webmaster

- Worked with a professional web developer to build a simpler, more functional new website

2014 - 2015 **Oxford University Lawn Tennis Club Men's Blues Captain**

- Realised that our training time wasn't compatible with our academic workload so worked with the coach to restructure our time on court and manage player's work loads
- Added multiple fixtures to our Summer schedule
- First Oxford Men's Blues Captain to win The Varsity Match in a decade

2013 - 2014 **Oxford University Lawn Tennis Club Treasurer**

- Wrote the club's accounting system in excel
- Delivered a 50% increase in membership subscriptions by simplifying membership sign up
- Established trade accounts with Head Tennis and Apollo Leisure

2009 - 2011 **Wesley College Prefect - Adam House Captain in 2011**

- Elected by my peers to lead Adamson in the House Cup
- Co-ordinated team's for both weekly competitions and longer term projects e.g. rock Eisteddfod

Selected Media

May 2022 **Climate Foresight Article**

- Quotes on overshoot https://www.climateforesight.eu/future-earth/climate-overshoot/

April 2022 **Coverage following Meinshausen et al., *Nature* (2022)**

- Austria Presse Agentur https://science.apa.at/power-search/17464260111046171060
- CNET https://www.cnet.com/science/climate/limiting-global-warming-to-just-below-2-degrees-possible-if-climate-pledges-met-in-full
- East Side Radio (Community Radio) https://eastsidefm.org/episodes/monday-drive-400pm-2nd-may-2022/

Aug 2021 **Radio following IPCC AR6 WG1**

- Radio Adelaide (Community Radio) Adelaide https://radioadelaide.org.au/2021/08/13/the-ipccs-warming-warnings/
- RRR (Community Radio) Melbourne https://www.rrr.org.au/explore/programs/breakfasters/episodes/17196-breakfasters-16-august-2021 (starts at 2:15)
- 4ZZZ (Community Radio) Brisbane https://4zzz.org.au/program/paradigm-shift (starts at 4:00)

Selected Public Seminars

Aug 2021 **A detailed look at future warming and remaining carbon budgets in the IPCC WG1 AR6 report**

- Online seminar (https://www.youtube.com/watch?v=aalLJsalhQE&t=1s)

Aug 2021 **Scenarios, carbon budgets and temperature projections in the new IPCC WG1 AR6 report**

- Online seminar (recording at https://www.youtube.com/watch?v=TRzV75SZLlY&t=8s)

Feb 2021 **On the state of reduced-complexity climate modelling**

- Online seminar (recording at https://www.youtube.com/watch?v=o3q40ktMJy8)

Apr 2018 **The Shared Socioeconomic Pathways (SSPs)**

- Online seminar (recording at https://www.youtube.com/watch?v=U91yjCqJtY4)

Selected Publications (ORCiD 0000-0002-4767-2723)

- Lead author IPCC AR6 WG1 Ch. 7 Supplementary Material
- Contributing author IPCC AR6 WG1 Technical Summary, Ch. 1, Ch. 4, Ch. 5, Ch. 6, Ch. 7 and Annex III
- Contributing author IPCC AR6 WG3 Summary for Policy Makers, Ch. 3, Annex C
- Nicholls, Z. R. J. et al.: Reduced Complexity Model Intercomparison Project Phase 2: Synthesising Earth system knowledge for probabilistic climate projections, Earth's Future, 9, e2020EF001900, https://doi.org/10.1029/2020EF001900, 2021.
- Nicholls, Z. R. J. et al.: Reduced Complexity Model Intercomparison Project Phase 1: introduction and evaluation of global-mean temperature response, Geosci. Model Dev., 13, 5175-5190, https://doi.org/10.5194/gmd-13-5175-2020, 2020.
- Nicholls, Z. R. J. et al.: Regionally aggregated, stitched and de-drifted CMIP-climate data, processed with netCDF-SCM v2.0.0, Geosci Data J., 00, 1-45, https://doi.org/10.1002/gdj3.113, 2021.

- Matthews, H. D., Tokarska, K. B., Nicholls, Z. R. J., et al.: Opportunities and challenges in using remaining carbon budgets to guide climate policy, Nature Geoscience, 13, 769-779, https://doi.org/10.1038/s41561-020-00663-3, 2020.
- Nicholls, Z. R. J., Gieseke, R., Lewis, J., Nauels, A., and Meinshausen, M.: Implications of non-linearities between cumulative CO2 emissions and CO2-induced warming for assessing the remaining carbon budget, Environ. Res. Lett., 15, 074017, https://doi.org/ 10.1088/1748-9326/ab83af, 2020.
- Meinshausen, M., Nicholls, Z. R. J., et al.: The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500, Geosci. Model Dev., 13, 3571-3605, https://doi.org/10.5194/gmd-13-3571-2020, 2020.
- Rogelj, J., Huppmann, D., Krey, V., Riahi, K., Clarke, L., Gidden, M., Nicholls, Z. and Meinshausen, M.: A new scenario logic for the Paris Agreement long-term temperature goal, Nature, 573 (7774), 357-363, https://doi.org/10.1038/s41586-019-1541-4, 2019.
- Millar, R. J., Nicholls, Z. R., Friedlingstein, P., and Allen, M. R.: A modified impulse-response representation of the global near-surface air temperature and atmospheric concentration response to carbon dioxide emissions, Atmos. Chem. Phys., 17, 7213-7228, https://doi.org/10.5194/acp-17-7213-2017, 2017.

Additional Skills

- IT skills: Proficient OSX, Microsoft Office, C, Matlab, NCL, Python and bash; basic website development and management skills
- Languages: English (native speaker); French (second language), basic written and spoken; German (second language), moderate written and spoken

Academic Referees

- Malte Meinshausen, Director, Australian-German Climate & Energy College, University of Melbourne. [redacted]
- Myles Allen, Professor of Geosystem Science, Head of the Climate Dynamics Group, University of Oxford. [redacted]
- Douglas Wallace, IB Diploma Co-ordinator, Wesley College St.Kilda Road Campus.[redacted]

Personal Referees

- Marianne Stillwell, President Wesley College Council. [redacted]