Expert statement by dr. Lisette van Beek

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1. Introduction

1.1 My name is Lisette van Beek. I am employed at Utrecht University, Copernicus Institute of Sustainable Development. My professional address is Princetonlaan 8a, 3584 CB Utrecht.

1.2 I am a postdoctoral researcher with an expertise in climate politics, modelling and societal transformations. I am a social scientist with a background in environmental governance and Science and Technology Studies. I wrote my dissertation on the use of Integrated Assessment Models (IAMs) in climate politics,[1] supervised by professor Maarten Hajer and professor Detlef van Vuuren. Van Vuuren is the head of the IMAGE team, one of the key IAM teams that provide inputs to assessments of the Intergovernmental Panel on Climate Change (IPCC). Compared to other social scientists, my collaboration with Van Vuuren has enabled direct insights into the development and use of IAMs and allowed for a nuanced perspective on this issue.

1.3 I have conducted extensive research on the use of IAMs in climate policy and am now considered one of the key experts on this topic, as indicated by highly cited peer-reviewed articles.[2,3] My research has focused on the development of IAM scenarios, the use of IAM scenarios in IPCC reports and the influence of IAM scenarios on climate policymaking. I therefore have an adequate understanding of the qualities of IAMs, their shortcomings and their use in climate research and policy.

1.4 I was invited by Milieudefensie to write an expert statement on issues that are relevant to the case. I have not been asked to take a position in the judgment by the Hague District Court on 26 May 2021, but I have noted the judgment, the two expert statements by professor Hawkes issued on 17 March 2022 and 15 December 2023, and the Memorie van Antwoord issued by Milieudefensie on 18 October 2022. I have been asked to reflect on the following issues that are relevant to the case: 1) the characteristics and applications of IAMs (section 2), 2) the use of IAMs in developing mitigation pathways (section 3), 3) the key contributions of IAM analyses in climate policy (section 4), and 4) the limitations of IAMs and the implications for assumed distribution of emission reductions and interregional equity (section 5). I conclude with summarizing the key take-aways from this expert statement (section 6).

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[1] Van Beek, L. M. G. (2023). *Persuasive Pathways: The Practice of Integrated Assessment Modelling in Climate Politics* (Doctoral dissertation, Utrecht University). https://dspace.library.uu.nl/handle/1874/432478

[2] Van Beek, L., Hajer, M., Pelzer, P., van Vuuren, D., & Cassen, C. (2020). Anticipating futures through models: the rise of Integrated Assessment Modelling in the climate science-policy interface since 1970. *Global Environmental Change, 65*, 102191.

[3] Van Beek, L., Oomen, J., Hajer, M., Pelzer, P., & van Vuuren, D. (2022). Navigating the political: An analysis of political calibration of integrated assessment modelling in light of the 1.5 C goal. Environmental Science & Policy, 133, 193-202.

1.5 I am not aware of any conflict of interest that could affect my suitability to act as an expert in this case. Everything I state in this report is based on reports of credible institutions such as the IPCC, academic peer-reviewed articles and policy documents, providing references to ensure transparency. When statements in this expert report reflect my own view, I will state this clearly.

2 The characteristics and applications of IAMs

2.1 Integrated Assessment Models (IAMs) are global computer simulation models that represent interactions between the climate system and socio-economic developments, such as land use, energy use and population growth. IAMs are developed by economists, earth and natural scientists, and engineers.[4] IAMs vary in model structure, complexity and detail. IAM modellers typically make a distinction between cost-benefit IAMs and detailed process IAMs.[5] Cost-benefit IAMs are more aggregated models that are used to assess costs and benefits of policies and the 'optimal' level of mitigation. Detailed process IAMs are more detailed in their representation of their physical and economic impacts, land-use and energy systems and regional and sectoral levels.[5] The latter type of IAMs is used to develop mitigation pathways and are the backbone of scenario analysis of the IPCC Working Group III. [2,6] In what follows, I use the term 'IAM' to refer to detailed process IAMs, given the relevance of this type of IAM to the case.

2.2 Six IAMs have been most widely used in developing global mitigation pathways, and contributed most significantly to the IPCC Assessment Reports: IMAGE (PBL, The Netherlands), MESSAGE-GlOBIOM (IIASA, Austria), AIM (NIES, Japan), GCAM (PNNL, United States), REMIND-MagPie (PIK, Germany) and WITCH-GOBIOM (RFF-CMCC, Italy).[2,6,9]

2.3 IAMs are typically applied to answer the following questions: 1) what are the implications of 'business-as-usual' trajectories on greenhouse gas (GHG) emissions?, 2) what are implications of the combined efforts of all countries' Nationally Determined Contributions (NDCs) on GHG emissions?, and 3) what are techno-economic strategies that would be required to achieve a given emission or temperature target at minimum costs? [4,5]

3 The use of IAMs to develop mitigation pathways

3.1 IAMs are explicitly designed to inform climate policy.[4,5] IAMs are commonly recognized as the primary tools to assess global mitigation pathways that meet the Paris Agreement goals, given global scale, sectoral scope (incorporating different mitigation sectors and interactions between sectors) and long-term scale (usually projecting scenarios until 2100 or 2050 on a global level).[2]

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[4] Bosetti, V. (2021). Integrated assessment models for climate change. In *Oxford research encyclopedia of economics and finance*. Oxford University Press.
[5] Weyant, J. (2017). Some contributions of integrated assessment models of global climate change. *Review of Environmental Economics and Policy*
[6] Gambhir, A., Butnar, I., Li, P. H., Smith, P., & Strachan, N. (2019). A review of criticisms of integrated assessment models and proposed approaches to address these, through the lens of BECCS. *Energies*, *12*(9), 1747

Since its first Assessment Report, IAMs have been the backbone of scenario analysis of IPCC Working Group III,[1,2,5] which is tasked with exploring response strategies. They are also the primary tools for assessing the combined progress of countries' pledges to achieve the Paris goals, which are reported in the annual UNEP Emission Gap reports.

3.2 In order to develop mitigation scenarios, IAM modelers need to make assumptions on key socio-economic parameters that are relevant to mitigation including population, energy use and production, urbanization, GDP and agriculture and land-use.[7] IAM modellers have developed a scenario framework with five global pathways that contain shared assumptions on these parameters: the Shared Socio-economic Pathways (SSPs). The SSPs represent five narratives of global trajectories, reflecting a 2x2 matrix with four narratives that vary from low to high 'challenges to mitigation' and low to high 'challenges to adaptation' and one narrative representing a 'middle-of-the-road' scenario. The SSPs range from low (SSP1) to intermediate (SSP2) to very high emissions trajectories (SSP5).[8] The SSPs were developed by the six major IAM teams described in section 2.2 in consultation with other experts.[9]

3.3 The SSPs are used by IAM teams to develop mitigation pathways that underly the IPCC WGIII. Because of the shared assumptions, the SSPs allow for model intercomparisons between different IAM teams and to assess the 'robustness' of IAM analyses across different IAM models.[9] The SSPs are also used by Earth System Modellers (underlying IPCC WGI) and researchers that assess climate impacts and vulnerability (underlying IPCC WGII), and as such allow for interaction, comparison and consistency between IPCC's Working Groups. The SSP scenario framework has been extensively used in IPCC AR5 (2014) and IPCC AR6 (2023) and the IPCC Special Report on 1.5°C (2018). In the latest IPCC Assessment Report (IPCC AR6, 2023),[10] the SSPs are used to assess climate impacts, impacts and risks by WGI and WGII as well as to assess mitigation scenarios by WGIII (IPCC AR6, 2023, Box SPM.1).

3.4 IAMs are designed to explore scenarios that meet global climate targets in the most cost-effective manner.[4,5] It varies between models how this cost-optimization is achieved: some IAMs measure the total present value cost of a low-carbon energy system that is consistent with the Paris Agreement Goals while others account for changes in prices and outputs across different economic sectors that result from changing energy costs.[5] Cost-effectiveness plays an important role in the IAM scenarios underlying the IPCC AR6 (2023), but the particular application of cost-

[7] Van Vuuren, D. P., Riahi, K., Calvin, K., Dellink, R., Emmerling, J., Fujimori, S., ... & O'Neill, B. (2017). The Shared Socio-economic Pathways: Trajectories for human development and global environmental change. *Global Environmental Change*, *42*, 148-152.

[8] O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., ... & Solecki, W. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global environmental change*, *42*, 169-180.

[9] Riahi, K., Van Vuuren, D. P., Kriegler, E., Edmonds, J., O'neill, B. C., Fujimori, S., ... & Tavoni, M. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global environmental change, 42, 153-168.

[10] IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland

effectiveness differs between the modelled scenarios. The majority of the IAM-scenarios that are used in the AR6 (IPCC, 2023),[10] assume a global carbon price. The global carbon price is used by IAM modellers as a tool (proxy) to represent the level of effort in mitigation policies when exploring cost-effective scenarios, rather than as a real-world policy instrument, because global IAMs typically lack the specificity of country-level mitigation measures.[11] As stated by the IPCC (2022), *'In modelled pathways, regional investments are projected to occur when and where they are most cost-effective to limit global warming. The model quantifications help to identify high-priority areas for cost-effective investments, but do not provide any indication on who would finance the regional investments.'* (p. 47).[12] In other words, cost-effectiveness is assumed in the IPCC AR6 scenarios to determine the regional distribution of mitigation investments. About half of the IPCC AR6 scenarios not only assume cost-effectiveness to determine regional distribution of mitigation investments, but also assume that mitigation targets are achieved in a *completely least-cost* manner (see Box SPM1, IPCC, 2022, p. 21).[12] Other IPCC AR6 scenarios that do not assume this completely least-cost mitigation are for example scenarios that assess existing policies or scenarios that assume and emphasize demand-side reductions. For example, the Low Energy Demand scenario (Grubler et al., 2018),[13] which is one of the 'Illustrative Mitigation Pathways' in the IPCC AR6, does not assume that the 1.5°C is achieved in a completely least-cost manner, but rather that strong reductions are achieved in energy demand. Yet, the scenario uses carbon pricing as a tool to determine how the transformation of the energy supply is achieved in a cost-effective manner. In sum, although its particular application differs, cost-effectiveness plays an important role in IAM scenarios, including the IPCC AR6 scenarios.

3.5 IPCC AR6 scenarios also vary in their assumed level of overshoot. 'Overshoot' means that pathways temporarily overshoot temperature targets but then return to the targeted level of global warming by removing carbon from the atmosphere. The C1 scenarios of IPCC AR6 assume that global warming is limited to 1.5°C with a >50% probability with no or limited overshoot. As stated by the IPCC (2022),[12] pathways that are associated with high overshoot *'imply increased climate-related risk, and are subject to increased feasibility concerns, and greater social and environmental risks, compared to pathways that limit warming to 1.5°C (>50%) with no or limited overshoot. (high confidence)'* (p. 15). Carbon dioxide removal (CDR) measures, most notably bioenergy with carbon capture and storage (BECCS) and afforestation, can have adverse environmental and socio-economic impacts, including biodiversity loss, food and water insecurity

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[11] Recently, a few IAM studies have also explored the effects of real-world policies, such as in Roelfsema, M., van Soest, H. L., den Elzen, M., de Coninck, H., Kuramochi, T., Harmsen, M., ... & van Vuuren, D. P. (2022). Developing scenarios in the context of the Paris Agreement and application in the integrated assessment model IMAGE: a framework for bridging the policy-modelling divide. *Environmental Science & Policy*, 135, 104-116.

[12] 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

[13] Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D. L., ... & Valin, H. (2018). A low energy demand scenario for meeting the 1.5 C target and sustainable development goals without negative emission technologies. *Nature energy*, *3*(6), 515-527.

(IPCC, 2022, p. 36).[12] I describe the reliance of IAMs on CDR in section 5.4.2.

4 Key contributions of IAM analyses in climate policy

4.1 Over the past decades, IAMs have made fundamental contributions to climate policymaking on the global and national scale. Three contributions of IAMs are particularly noteworthy: agenda-setting, target-setting and mitigation analysis.[1,2]

4.2 In the early 1990s, IAM scenarios have been foundational in putting climate change on the global political agenda, most notably through their business-as-usual scenarios which raised awareness of the adverse implications of current emissions trajectories.[1,2,5]

4.3 IAM analyses were also paramount in setting global climate targets. IAM pathways towards the 1.5°C and 2°C degrees targets were invaluable to gain political support for the Paris Agreement goals.[1,2,3,14,15] IAM scenarios to meet the 1.5°C target, in particular those presented in the Special Report on 1.5°C degrees (IPCC, 2018), estimated a required emission reduction of net-zero by 2050 and 45% by 2030, which have stimulated mid-century 'net-zero' emissions targets that have been set by numerous countries, cities and businesses worldwide.[3]

4.4 IAM analyses also contribute to national climate policy, for example by determining net-zero emission targets.[16] The past few years witnessed a proliferation of projects where IAMs are used to explore mitigation scenarios on the country level, such as the Deep Decarbonization Project,[17] the COMMIT project,[18] the ENGAGE project,[19] and the ELEVATE project.[20]

4.5 To conclude, IAMs have various analytical qualities (section 2). In my view, these qualities make IAMs appropriate tools to assess the total required reduction of global emissions under the 1.5°C target. IAMs also made several important contributions to climate research and policy (section 3 and 4). However, the specific assumptions underlying IAM analyses are heavily debated in academic literature and the limitations of IAMs are recognized by the IPCC. Some of these limitations are relevant to the case as they have implications for the distribution of mitigation efforts and equity (section 5).

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[14] Cointe, B., & Guillemot, H. (2023). A history of the 1.5° C target. *Wiley Interdisciplinary Reviews: Climate Change*, *14*(3), e824.

[15] Livingston, J. E., & Rummukainen, M. (2020). Taking science by surprise: The knowledge politics of the IPCC Special Report on 1.5 degrees. *Environmental Science & Policy*, *112*, 10-16.

[16] Pye, S., Li, F. G., Price, J., & Fais, B. (2017). Achieving net-zero emissions through the reframing of UK national targets in the post-Paris Agreement era. Nature energy, 2(3), 1-7

[17] https://ddpinitiative.org/

[18] https://www.pbl.nl/en/archive/commit

[19] https://www.engage-climate.org/

[20] https://cordis.europa.eu/project/id/101056873

5 Limitations of IAMs as reported in the academic literature and recognized by the IPCC

5.1 In this section I describe the key limitations of IAMs that are relevant to the case, based on existing academic reviews of IAM limitations that have appeared in the last decade[6,21,22] as well as the limitations that are recognized by the IPCC (2022, 2023).[10,12]

5.2 I consider the following aspects relevant to the case: 1) the reliance of IAM pathways on cost-effectiveness, which disregards interregional equity principles (section 5.3), 2) limited representation of feasibility of mitigation measures (section 5.4), 3) the use of discount rates in global mitigation pathways, which disregards intergenerational equity principles (section 5.5) and 4) limited representation of (non-linear and catastrophic) climate impacts (5.6).

5.3 The reliance of IAM pathways on cost-effectiveness disregards interregional equity principles

5.3.1 As described in section 3.4, in IAM scenarios, including the C1 scenarios in IPCC AR6 (2023),[10] cost-effectiveness plays an important role in exploring mitigation pathways (by assuming a global carbon price or even assuming a completely least-cost pathway) and do not address equity considerations. This reliance on cost-effectiveness disregards interregional equity principles underlying the UNFCCC (1992) and the Paris Agreement (2015). In the IPCC AR6 (2022),[12] it is stated that *'Most [models] do not make explicit assumptions about global equity, environmental justice or intra-regional income distribution.'* (p. 21).

5.3.2 The reliance on cost-effectiveness is one of the major criticisms on IAMs.[21,22] One of the main reasons for critique is that it disregards interregional equity principles.[21] In the following sections, I elaborate on the interregional equity principles underlying UNFCCC agreements (5.3.3), the ways in which IAM pathways disregard these principles (5.3.4), the unrealistic assumptions of interregional financial transfers (5.3.5), the growing scientific consensus on equity principles to guide mitigation research (5.3.6) and the implications of cost-effective vs. equity-based IAM scenarios for regional distribution of emission reduction efforts (5.3.7). I use the example of India vs. OECD countries to illustrate the injustices that are implied in IAM scenarios (5.3.8).

5.3.3 In the UNFCCC (1992), Parties have agreed to *'protect the climate system for the benefit of present and future generations of humankind, on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities'* (Article 3.1). In this Convention, Parties have further agreed that *'The developed country Parties and other Parties included in Annex I commit themselves specifically as provided for in the following: (a)*

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[21] Rivadeneira, N. R., & Carton, W. (2022). (In) justice in modelled climate futures: A review of integrated assessment modelling critiques through a justice lens. Energy Research & Social Science, 92, 102781.
[22] Keppo, I., Butnar, I., Bauer, N., Caspani, M., Edelenbosch, O., Emmerling, J., ... & Wagner, F. (2021). Exploring the possibility space: Taking stock of the diverse capabilities and gaps in integrated assessment models. Environmental Research Letters, 16(5), 053006.

Each of these Parties shall adopt national policies and take corresponding measures on the mitigation of climate change, by limiting its anthropogenic emissions of greenhouse gases and protecting and enhancing its greenhouse gas sinks and reservoirs. These policies and measures will demonstrate that developed countries are taking the lead in modifying longer-term trends in anthropogenic emissions consistent with the objective of the Convention[..]' (Article 4.2). The principle of Common but Differentiated Responsibilities (CBDR) is also a key principle in the Paris Agreement (UNFCCC, 2015), in which Parties have also committed to combat climate change 'on the basis of equity' (Article 4.1) and that *'Developed country Parties should continue taking the lead by undertaking economy-wide absolute emission reduction targets. Developing country Parties should continue enhancing their mitigation efforts, and are encouraged to move over time towards economy-wide emission reduction or limitation targets in the light of different national circumstances.'* (Article 4.4).

5.3.4 In IAM-pathways towards climate targets that assume a global carbon price, it is generally assumed that mitigation is cheaper to realize in developing countries compared to developed countries. One reason is that coal phase-out is generally assumed to be more cost-effective than other mitigation efforts, and non-OECD countries rely more heavily on coal compared to OECD countries.[23] In particular, China, India and South Africa heavily depend on coal. This is illustrated in Figure 1, which was copied from the IPCC AR6 WGIII (2022, p. 686).[12] The figure shows the regional emission reductions from energy across six global regions as assumed in the IAM scenarios underlying the report. It shows that in the C1 scenarios (with no or limited overshoot and a >50% chance of limiting global warming to 1.5°C), developed countries ('OECD+EU') would reduce emissions from energy more slowly compared to Asia ('ASIA') and Latin America and the Caribbean ('LAM'). It also shows that Africa ('AFRICA') should reduce its emissions from energy at about the same speed as developed countries ('OECD+EU'). Cost-effective IAM scenarios also model relatively larger amounts of CDR and emission reductions from Agriculture, Forestry, and Other Land Uses (AFOLU) in developing countries compared to developed countries. In sum, IAM scenarios, including the C1 scenarios in IPCC AR6, typically assume that stronger emission reduction is achieved in developing countries compared to developed countries. This assumption is the exact opposite of the CBDR principle underlying the UNFCCC (1992) and the Paris Agreement (2015), in which Parties agreed that developed countries will take the lead in mitigating climate change by reducing their national emissions (see section 5.3.3). Therefore, in my view, the reliance of IAMs on cost-effectiveness is not well-justified, in contrast to what is argued by Prof. Hawkes in his expert statement of 15 December 2023 (section 6).

[23] World Energy Balances 2023 (IEA, 2023); https://www.iea.org/data-and-statistics/data-product/world-energy-balances

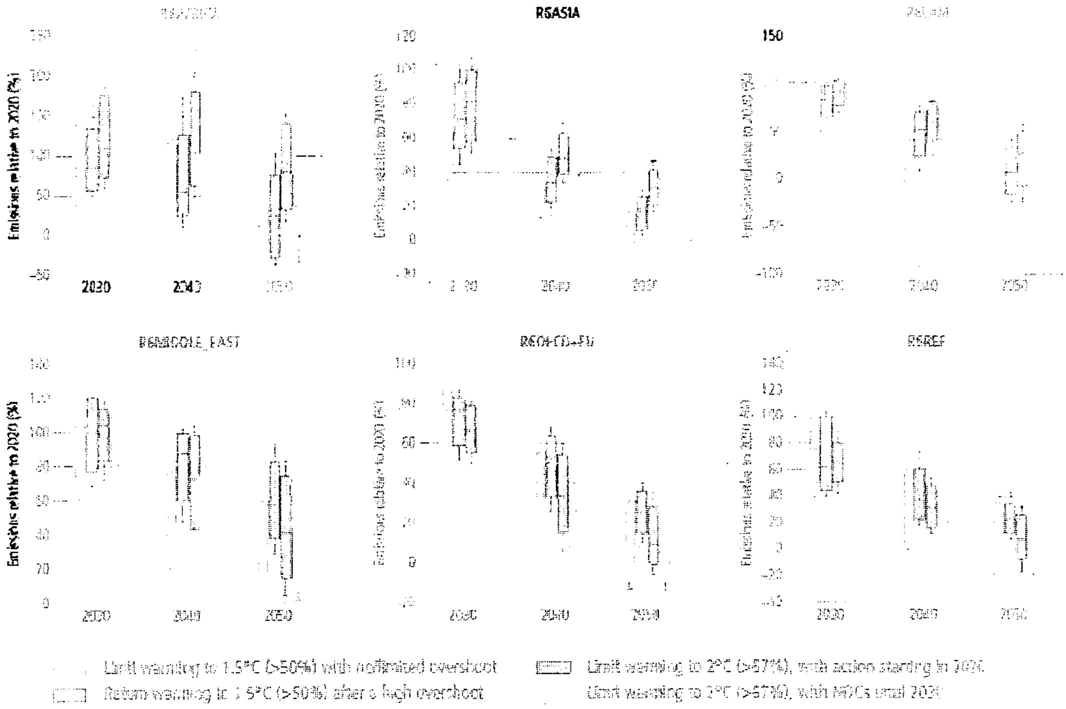

Figure 1. **Net regional CO2 emissions from energy across scenarios**. Boxes indicate 25th and 75th percentiles, while whiskers indicate 5th and 95th percentiles. Regions: Asia (ASIA), Latin America and Caribbean (LAM), Middle East (MIDDLE_EAST), Africa (AFRICA), Developed Countries (OECD 90 and EU) (OECD+EU) and Reforming Economies of Eastern Europe and the Former Soviet Union (REF). Most mitigation scenarios are based on a cost-minimising framework that does not consider historical responsibility or other equity approaches. Source: IPCC WGIII Figure 6.27, p. 686.

5.3.5 Some IAM studies assume that the injustices resulting from cost-effective mitigation pathways could be compensated by means of interregional financial transfers.[24] Apart from the fact that this assumption is not in line with the UNFCCC (1992) and the Paris Agreement (2015), in which countries agreed to develop mitigation policies within their own territory and submit these in the form of NDCs and long-term mitigation strategies, it is also not a realistic assumption. In order for cost-effective mitigation pathways to align with equity principles, extraordinary interregional financial transfers would be required (ranging from USD 250 billion to 1581 trillion annually depending on the equity principle applied).[25] It is not realistic to assume that sufficient financial transfers will be established to account for these injustices. To date, even the much smaller pledges that developed countries have made in the UNFCCC negotiations to financially assist developing countries in their mitigation efforts have not been met. In COP16 in Copenhagen in 2009, developed nations committed to mobilize USD 100 billion on a yearly basis to support developing countries in their mitigation and adaptation efforts. As assessed by the OECD in 2023, this target has been missed systematically, with

[24] Bauer, N., Bertram, C., Schultes, A., Klein, D., Luderer, G., Kriegler, E., ... & Edenhofer, O. (2020). Quantification of an efficiency–sovereignty trade-off in climate policy. Nature, 588(7837), 261-266.
[25] Pachauri, S., Pelz, S., Bertram, C., Kreibiehl, S., Rao, N. D., Sokona, Y., & Riahi, K. (2022). Fairness considerations in global mitigation investments. *Science*, *378*(6624), 1057-1059.

actual financial transfers varying between USD 52.4 and 89.6 annually between 2013 and 2021.[26] It is important to note that this commitment to mobilize USD 100 billion to support developing countries in their mitigation and adaptation efforts is additional to, and not a replacement of, the principle that developed countries take the lead in mitigating climate change by reducing their national emissions.

5.3.6 There is a growing scientific consensus that equity principles that are in line with the UNFCCC (1992) and Paris Agreement (2015) are more adequate guiding principles for mitigation analysis than cost-effectiveness. In 'effort sharing' or 'burden sharing' studies, which assess the fair allocation of the carbon budget across regions, a distinction is usually made between 1) *equality*: allocation of the carbon budget is proportional to current emission shares ('grandfathering') or current per capita emissions ('per capita convergence'), 2) *responsibility*: the carbon budget is allocated based on historic emissions, 3) *capability*, the carbon budget allocation is based on the financial capacity to take climate measures 4) *needs*, prioritizing the worlds' poorest to meet basic needs and 5) *cost-effectiveness*, allocation based on cost-optimal allocation.[27,28,29,30] Among those principles, cost-effectiveness is generally not viewed as a fair principle to allocate the carbon budget.[27] Even IAM modellers themselves state that *'cost-optimal approaches do not lead to outcomes that can be regarded as fair according to most effort-sharing approaches.'* (Van den Berg et al., 2019, p. 1805).[30] Allocation of the carbon budget based on current emissions (grandfathering) is also generally viewed as an unfair principle. Climate change disproportionally impacts developing countries compared to developing countries (IPCC, 2023),[10,31,32,33] while these countries have contributed the least to historic global CO_2 emissions (IPCC, 2022, p. 65).[12,34] It is also misaligned with the CBDR principle underlying UNFCCC agreements (see section 5.3.3). Among the equity principles, 'responsibility', 'capability' and 'needs' are generally viewed as most in line with UNFCCC agreements.[27]

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[26] OECD (2023). Climate finance provided and mobilised by developed countries in 2013-2021 Available at https://www.oecd-ilibrary.org/docserver/e20d2bc7-en.pdf?expires=1707236162&id=id&accname=oid043801&checksum=F9BC6254D8CE5E9B93892E3A42D84085
[27] Dooley, K., Holz, C., Kartha, S., Klinsky, S., Roberts, J. T., Shue, H., ... & Singer, P. (2021). Ethical choices behind quantifications of fair contributions under the Paris Agreement. *Nature Climate Change*, *11*(4), 300-305.
[28] Pan, X., den Elzen, M., Höhne, N., Teng, F., & Wang, L. (2017). Exploring fair and ambitious mitigation contributions under the Paris Agreement goals. *Environmental Science & Policy*, *74*, 49-56.
[29] Fyson, C. L., Baur, S., Gidden, M., & Schleussner, C. F. (2020). Fair-share carbon dioxide removal increases major emitter responsibility. *Nature Climate Change*, *10*(9), 836-841.
[30] Van den Berg, N. J., van Soest, H. L., Hof, A. F., den Elzen, M. G., van Vuuren, D. P., Chen, W., ... & Blok, K. (2020). Implications of various effort-sharing approaches for national carbon budgets and emission pathways. Climatic Change, 162, 1805-1822.
[31] Taconet, N., Méjean, A., & Guivarch, C. (2020). Influence of climate change impacts and mitigation costs on inequality between countries. *Climatic Change*, *160*, 15-34.
[32] Diffenbaugh, N. S. & Burke, M. Global warming has increased global economic inequality. *Proc. Natl Acad. Sci. USA* **116**, 9808–9813 (2019).
[33] Burke, M., Hsiang, S. M. & Miguel, E. Global non-linear effect of temperature on economic production. *Nature* **527**, 235–239 (2015).
[34] Jones, M. W., Peters, G. P., Gasser, T., Andrew, R. M., Schwingshackl, C., Gütschow, J., ... & Le Quéré, C. (2023). National contributions to climate change due to historical emissions of carbon dioxide, methane, and nitrous oxide since 1850. *Scientific Data*, *10*(1), 155.

5.3.7 There is a growing body of IAM studies that explores the implications of different equity principles for the international allocation of the remaining carbon budget.[2,28,29,30,35] These studies systematically report that applying equity principles including responsibility, capability and needs result in much stronger reductions in OECD countries compared to reductions that are assumed in cost-effective IAM scenarios. For example, one IAM study found that some of those equity principles can even result in negative carbon budgets for the EU and USA while China and India would be allocated 80% of the remaining carbon budget under a 2°C scenario.[30] Given that OECD countries rely less heavily on coal and more heavily on gas and oil compared to non-OECD countries, this would automatically imply more rapid reductions in oil and gas compared to what is typically assumed in IAM scenarios, including the C1 scenarios presented in the IPCC AR6 (2023).[10]

5.3.8 In this section, I illustrate the injustices that are implied in cost-effective IAM scenarios by giving the example of India vs. OECD countries. The example was also used by Prof. Hawkes in his expert statement of 17 March 2022. Over 80% of the energy needs in India are supplied by coal, oil and biomass, of which coal is the largest fuel in the energy mix and solar energy is on the rise. India is the third-largest emitter of CO_2, but their per capita CO_2 emissions are very low.[36] In 2022, per capita CO_2 emissions of India were 1.6 tonnes, which is significantly lower compared to OECD countries (e.g. 13.0 tonnes in the USA, 14.8 tonnes in Australia, 7.3 tonnes in Germany, 7.5 tonnes in the Netherlands).[37] India has also historically contributed significantly less to global emissions compared to OECD countries.[38] Asian countries are also more severely affected by climate hazards such as droughts, heat stress and floods compared to countries in Europe and North America (IPCC AR6 WGII, figure 16.3).[39] As noted by Prof. Hawkes in his expert statement, India also faces substantial institutional and socio-economic barriers to coal phase-out. Recent studies on the socio-economic implications of coal phase-out in India found that coal-phase out would disproportionally impact the poorest districts in India, which will face severe employment losses.[40,41] A recent study compared 'energy transition readiness' across 14 countries including India and a number of European countries using diverse social, institutional, economic and technological criteria.[42]

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[35] Chen, X., Yang, F., Zhang, S., Zakeri, B., Chen, X., Liu, C., & Hou, F. (2021). Regional emission pathways, energy transition paths and cost analysis under various effort-sharing approaches for meeting Paris Agreement goals. *Energy, 232,*

[36] IEA (2021), *India Energy Outlook 2021*, IEA, Paris https://www.iea.org/reports/india-energy-outlook-2021, Licence: CC BY 4.0

[37] World Bank (2020), available at: https://data.worldbank.org/indicator/EN.ATM.CO2E.PC?view=map

[38] Jones, M. W., Peters, G. P., Gasser, T., Andrew, R. M., Schwingshackl, C., Gütschow, J., ... & Le Quéré, C. (2023). National contributions to climate change due to historical emissions of carbon dioxide, methane, and nitrous oxide since 1850. *Scientific Data, 10*(1), 155.

[39] IPCC, 2022: *Climate Change 2022: Impacts, Adaptation, and Vulnerability.* Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., doi:10.1017/9781009325844

[40] Ordonez, J. A., Jakob, M., Steckel, J. C., & Ward, H. (2023). India's just energy transition: Political economy challenges across states and regions. *Energy Policy, 179*, 113621.

[41] Agrawal, K., Pathak, M., Jana, K., Unni, J., & Shukla, P. (2024). Just transition away from coal: Vulnerability analysis of coal districts in India. *Energy Research & Social Science, 108*, 103355.

[42] Neofytou, H., Nikas, A., & Doukas, H. (2020). Sustainable energy transition readiness: A multicriteria assessment index. *Renewable and Sustainable Energy Reviews, 131*, 109988.

This study found high readiness in Sweden, Western Europe and Canada, and relatively low readiness in India and Indonesia. On all criteria, the Netherlands scored higher on energy transition readiness compared to India. All these findings exemplify that the reliance on cost-effectiveness by IAM scenarios, including the C1 scenarios in IPCC AR6,[10] and the assumed emission reductions and speed of coal phase-out in these scenarios, are highly unjust and not in line with interregional equity principles underlying UNFCCC agreements.

5.4 Limited representation of real-world feasibility of mitigation measures

5.4.1 A second major criticism of IAMs is their limited representation of the real-world feasibility of mitigation measures, most notably CDR.[6] IAM scenarios, including those represented in IPCC assessments, have been criticized for being too optimistic about CDR,[43,44,45] coal phase-out,[46,47] and Agriculture, Forestry and other Land Uses (AFOLU),[48] while being too pessimistic about solar PV.[49,50] Here I only elaborate on criticism on the feasibility of CDR (section 5.4.2) and coal phase-out (section 5.4.3), given the relevance to the case.

5.4.2 The reliance on CDR, most notably BECCS, is a major criticism of IAMs.[6] There is a wide variety of CDR methods, such as afforestation, BECCS, Direct Air Capture and Storage (DACCS), peatland and coastal wetland restoration and ocean fertilization (see IPCC, 2022, p. 1262 for an overview).[12] IAM scenarios represented in IPCC AR6 mostly rely on BECCS and afforestation (IPCC, 2022, 2023).[10,12] Scholars have questioned the real-world feasibility of the large-scale deployment of CDR that is assumed in IAM pathways, most notably BECCS.[41,42,43] The IPCC (2022) also notes that the demonstration and deployment of BECCS is limited in scale (p. 1261).[12] The CDR methods that IAMs rely most strongly on, BECCS and afforestation, are associated with substantial environmental and socio-economic risks, including food and water security, biodiversity and Indigenous rights (IPCC, 2022, p. 36).[12] This is mainly due to the required amount of land that is necessary for these methods and the resulting land competition with food production and ecosystems (IPCC, 2022, p. 115).[12] The real-world feasibility of CDR, which takes socio-economic and environmental feasibility into account, would thus result in lower potentials of CDR than what is typically assumed in IAM pathways. Recently, the International Institute of Sustainable Development (IISD) published a

[43] Anderson, K., & Peters, G. (2016). The trouble with negative emissions. Science, 354(6309), 182-183.
[44] Vaughan, N. E., & Gough, C. (2016). Expert assessment concludes negative emissions scenarios may not deliver. *Environmental research letters*, *11*(9), 095003.
[45] Grant, N., Gambhir, A., Mittal, S., Greig, C., & Köberle, A. C. (2022). Enhancing the realism of decarbonisation scenarios with practicable regional constraints on CO2 storage capacity. *International Journal of Greenhouse Gas Control*, *120*, 103766.
[46] Vinichenko, V., Cherp, A., & Jewell, J. (2021). Historical precedents and feasibility of rapid coal and gas decline required for the 1.5° C target. *One Earth*, *4*(10), 1477-1490.
[47] Muttitt, G., Price, J., Pye, S., & Welsby, D. (2023). Socio-political feasibility of coal power phase-out and its role in mitigation pathways. Nature Climate Change, 13(2), 140-147.
[48] Roe, S., Streck, C., Beach, R., Busch, J., Chapman, M., Daioglou, V., ... & Lawrence, D. (2021). Land-based measures to mitigate climate change: Potential and feasibility by country. Global Change Biology, 27(23), 6025-6058.
[49] Creutzig, F., Agoston, P., Goldschmidt, J. C., Luderer, G., Nemet, G., & Pietzcker, R. C. (2017). The underestimated potential of solar energy to mitigate climate change. Nature Energy, 2(9), 1-9.
[50] Jaxa-Rozen, M., & Trutnevyte, E. (2021). Sources of uncertainty in long-term global scenarios of solar photovoltaic technology. Nature Climate Change, 11(3), 266-273.

report which assessed a selection of the IAM scenarios of IPCC AR6 towards the 1.5°C degree target and its implications for mitigation efforts across sectors and countries.[51] Out of the IPCC AR6 C1 scenarios, that limit global warming to 1.5°C (>50% chance) with no or limited overshoot, the IISD selected 26 scenarios based on the feasibility and sustainability of BECCS, fossil CCS and afforestation. The IISD only selected scenarios that did not exceed the threshold of 3 Gt/CO_2 per year for the potential of BECCS, which is assessed by the IPCC as the threshold for the onset of medium concerns about feasibility (IPCC, 2022, p. 147 and Annex III, table 8 on p. 1877).[12] Also, scenario's with more than 3.8 GtCO_2 per year for fossil CCS by 2050 were excluded, based on the same IPCC threshold for medium feasibility concerns. The scenarios that the IISD selected also did not exceed a reduction potential of 3.6 GtCO_2 per year for afforestation and reforestation, based on a widely cited study by Fuss et al. (2018)[52] that estimated the maximum *sustainable* potential of afforestation and reforestation. The IISD (2022) found that when feasibility and sustainability of BECCS and afforestation/reforestation were taken into account, this resulted in a reduction of oil and gas production and consumption of 30% by 2030. The modeled reductions in oil and gas in the selected scenarios by the IISD (2022) are significantly larger compared to the median of IPCC AR6 scenarios. A recently published study in *Science* (Deprez et al., 2024)[53] assesses the sustainable limits of CDR. The study assessed risks of biodiversity and other land-use impacts from BECCS, afforestation/reforestation and 'nature-based' CDR such as ecosystem restoration. Based on an elaborate assessment of sustainability risks, the authors estimated the potential of BECCS to be between 1.2 GtCO_2 per year and 2.8 GtCO_2 per year and the potential of afforestation/reforestation to be between 1.3 GtCO_2 and 3.8 GtCO_2 per year, as the range for the potential with medium sustainability risks. As stated by the authors, *'We consider that these upper bounds of medium risk indicate the limit between acceptable and unacceptable impacts; if exceeded, there are high risks to biodiversity, water availability, biogeochemical cycles, and competition for food production'* (p. 484).

5.4.3 The feasibility of coal-phase out as assumed in IAM scenarios is also challenged. A recent study published in *Nature Climate Change* (Muttit et al., 2023)[47] analyzed the socio-political feasibility of coal phase-out in mitigation pathways. The study finds that the assumed coal reductions in IPCC AR6 scenarios are mainly achieved in countries that heavily rely on coal, which are China, India and South Africa. Apart from the interregional equity implications of the assumed mitigation efforts in these countries (section 5.3), the study finds that the assumed speed of coal phase-out in IPCC AR6 scenarios does not reflect socio-political feasibility. Socio-political feasibility usually refers to a range of social and political factors that determine the speed of transitions, such as the political influence of affected actors (workers,

[51] IISD (2022) Lighting the Path: What IPCC energy pathways tell us about Paris-aligned policies and investments. Available at: https://www.iisd.org/publications/report/ipcc-pathways-paris-aligned-policies
[52] Fuss, Sabine, William F. Lamb, Max W. Callaghan, Jérôme Hilaire, Felix Creutzig, Thorben Amann, Tim Beringer et al. "Negative emissions—Part 2: Costs, potentials and side effects." *Environmental research letters* 13, no. 6 (2018): 063002.
[53] Deprez, A., Leadley, P., Dooley, K., Williamson, P., Cramer, W., Gattuso, J. P.,... & Creutzig, F. (2024). Sustainability limits needed for CO2 removal. Science, 383(6682), 484-486.

companies, communities), social acceptance of technologies, economic effects and values of decision-makers. The study quantified socio-political feasibility as the fastest ever recorded historical energy transitions and compared the speed of coal phase-out according to the Powering Past Coal Alliance (which is in line with historic speed of energy transitions) to cost-effective scenarios towards the 1.5°C in the IPCC AR6. The study found that for cost-effective scenarios, *'For China, India and South Africa, coal declines around twice as fast as any decline seen for any country relative to its size'* (p. 141). This echoes earlier findings that half of the IPCC 1.5°C scenarios assume a faster coal phase-out in Asia than any energy transition ever witnessed in history.[46] The ignorance of socio-political feasibility of coal phase-out also has direct implications for the distribution of mitigation efforts between countries and sectors. When this socio-political feasibility was taken into account, this resulted in 50% more rapid emission reduction in the Global North compared to IPCC AR6 scenarios.[47] The authors found reductions in oil production in OECD countries up to 19% in 2030.[47] However, this scenario only focused on socio-political feasibility considerations and has neither taken into account equity considerations nor the above mentioned concerns about CDR.

5.4.4 An example of a scenario that takes into account regional equity as well as multiple feasibility considerations is the Net Zero Roadmap, also known as the NZE scenario, published by the International Energy Agency (IEA) in 2023.[54] With regard to feasibility and equity, the IEA states that *'The IEA tracks hundreds of thousands of energy sector datapoints that cover elements ranging from policy developments, technology deployment, investment and supply chains to infrastructure, innovation and costs. This data-driven approach feeds the model used to develop the NZE Scenario, which also factors in the various circumstances of individual countries and regions in great detail. This allows the NZE Scenario to take account of the feasibility of scaling up emissions reduction options at the speed and scale required across various regions, sectors and technologies, and to integrate concerns about equity.'* (p. 57). With regard to interregional equity, the IEA further notes that *'Different countries have varying starting points, capacities, and resource endowments. Differentiated pathways are delineated in the NZE Scenario as an essential design principle.'* (p. 59). And that *'Advanced economies take the lead and reach net zero emissions by around 2045 as a group, consistent with their higher financial capacities and responsibility in historical emissions.'* (p. 59). In other words, the scenario takes into account the interregional equity principles of 'responsibility' and 'capability' (see section 5.3.6), which are most in line with equity principles underlying the UNFCCC agreements. The assumption that advanced economies take the lead is also in line with the CBDR principle underlying UNFCCC agreements (section 5.3.3). Taking into account interregional equity, the IEA finds that *'emissions in advanced economies fall nearly two-times faster in the current decade than emissions in emerging market and developing countries.'* (p.

[54] IEA (2023). Net Zero Roadmap. A global pathways to keep the 1.5°C goal in reach. Available at: https://iea.blob.core.windows.net/assets/9a698da4-4002-4e53-8ef3-631d8971bf84/NetZeroRoadmap_AGlobalPathwaytoKeepthe1.5°CGoalinReach-2023Update.pdf.

59). Given that advanced economies rely more strongly on oil and gas whereas developing economies rely more heavily on coal, this finding also has implications for the assumed CO_2 emission reductions from oil, gas and coal. According to the NZE scenario (IEA, 2023),[54] CO_2 emission reductions from coal, oil and gas fall with respectively 46.7%, 27.8% and 22.7% between 2022 and 2030 (IEA, 2023, Table A.4 on page 198). However, the NZE scenario (IEA, 2023)[54] assumes relatively high CCS (6 Gt/year), which is higher than the medium threshold as defined by the IPCC (3.8 Gt/year). This may imply a need for even stronger reductions in coal, oil and natural gas than the NZE scenario (IEA, 2023) assumes. In sum, when multiple feasibility considerations as well as interregional equity principles are taken into account, assumed emission reductions from oil and gas in 2030 are significantly higher compared to what is typically assumed in IAM scenarios, including those in the IPCC AR6, as well as the scenario by Muttit et al. (2023).[47]

5.5 The use of discount rates in global mitigation pathways disregards intergenerational equity principles

5.5.1 The use of discount rates is a third major criticism of IAMs.[21] IAM scenarios use relatively high discount rates to assess the cost-effective mitigation pathways. These discount rates are not in line with intergenerational equity principles underlying the Paris Agreement. In this section I will describe what intergenerational equity is and how it is represented in the Paris Agreement (5.5.2), what discount rates are and how they are used in IAM-based mitigation pathways (5.5.3), how current discount rates disregard intergenerational equity (5.5.4), the growing scientific consensus on using lower discount rates (5.5.5) and the implications of lower discount rates for required emission reduction levels (5.5.6).

5.5.2 Intergenerational equity refers to the distribution of climate action and impacts between generations. Future generations will be disproportionally impacted by climate extremes, since climate impacts such as heat waves will most likely increase in frequency, duration, intensity and geographical scales over the next decades.[55] A recent study in *Science* estimated that *'children born in 2020 will experience a two- to sevenfold increase in extreme events, particularly heat waves, compared with people born in 1960, under current climate policy pledges'* (Thiery et al., 2021, p. 158).[55] In the Paris Agreement, it is stated that: *'Acknowledging that climate change is a common concern of humankind, Parties should, when taking action to address climate change, respect, promote and consider their respective obligations on human rights, the right to health, the rights of indigenous peoples, local communities, migrants, children, persons with disabilities and people in vulnerable situations and the right to development, as well as gender equality, empowerment of women* ***and***

[55] Thiery, W., Lange, S., Rogelj, J., Schleussner, C. F., Gudmundsson, L., Seneviratne, S. I., ... & Wada, Y. (2021). Intergenerational inequities in exposure to climate extremes. Science, 374(6564), 158-160.

intergenerational equity.' (emphasis added).

5.5.3 IAMs incorporate mainstream macroeconomic models and typically use discount rates in global mitigation pathways. A discount rate describes the extent to which something is valued less, 'discounted', in the future compared to today. Doing an investment now is thus perceived as more costly compared to an investment later in the future. Using positive discount rates in IAM analysis implies the following: 1) the well-being of current generations is valued more than the well-being of future generations, 2) future generations are expected to be wealthier than current generations, given the assumption of economic growth. Where cost-benefit IAMs use the discount rate to find the optimal balance of the costs and benefits on climate policies, detailed process IAMs use the discount rates to find the most cost-effective mitigation pathways that are in line with global climate targets (see also section 2.1). The latter use of the discount rate is particularly relevant to the case. IAM models typically use relatively high discount rates. Most IAMs that were used in the IPCC AR6 to assess global mitigation pathways use a discount rate of 3-5% (IPCC, 2022, p. 1875).[12] IAM models that were used in earlier IPCC assessments used even higher discount rates (5-6% per year).[56]

5.5.4 The choice of discount rates has significant implications for the timing of emission reductions and the assumed level of overshoot in global mitigation pathways.[56] As stated by the IPCC, *'Lower discount rates favour earlier mitigation, reducing reliance on CDR and temperature overshoot.'* (IPCC, 2022, p. 18).[12] The influence of discount rates is substantial: one percentage increase in the discount rate can result in up to 50% increase in overshoot.[56] The discount rates that IAMs currently use thus favor that mitigation is postponed to later in the century, shifting the burden of mitigation efforts to future generations. This is not in line with the intergenerational equity principle underlying the Paris Agreement (see section 5.5.2).

5.5.5 The use of discount rates by IAMs is a long debated issue the climate economics literature.[20,57,58] Two key conflicting views are between Nordhaus (2007),[58] who advocated for higher discount rates, implying delayed climate action, and Stern (2006),[57] who advocated for lower discount rates, favoring early action. In recent years, there is a growing scientific consensus that lower discount rates should be used in mitigation pathways. Recent expert elicitations on the appropriate levels of discount rates point to values around 2%.[59] A recent study also suggested that although more rapid emission reduction may require more investments in mitigation measures in the near-term, these investments will result in

[56] Emmerling, J., Drouet, L., van der Wijst, K. I., Van Vuuren, D., Bosetti, V., & Tavoni, M. (2019). The role of the discount rate for emission pathways and negative emissions. Environmental Research Letters, 14(10), 104008.
[57] Stern, N. (2006). The economics of climate change: the Stern Review. Cambridge University Press
[58] Nordhaus W 2007a Critical assumptions in the stern review on climate change Science 317 201–2
[59] Drupp, M. A., Freeman, M. C., Groom, B., & Nesje, F. (2018). Discounting disentangled. American Economic Journal: Economic Policy, 10(4), 109-134.

economic gains on the longer term.[60]

5.5.6 In general, it can be concluded that lower discount rates would imply more rapid near-term emission reductions compared to what is typically assumed in IAM scenarios, including those that are represented in IPCC AR6 (2023).

5.6 The limited representation of (non-linear and catastrophic) climate impacts

5.6.1 Another key criticism is the lack of representation of (non-linear and catastrophic) climate impacts.[6,22] This limitation has two key components: 1) the costs of climate damages are underestimated (5.6.2), 2) non-linear and catastrophic climate impacts are not taken into account (5.6.3).

5.6.2 First, IAMs typically underestimate the economic costs of climate impacts.[61,62,63,64] The IPCC (2022) also notes that most IAM pathways do not account for damages from climate change (p. 37).[12] The economic impacts of climate change include for example loss of agricultural productivity, infrastructure losses, and loss of labor productivity. Because IAM pathways typically do not take the economic costs of climate change into account, but focus only on the costs of mitigation, near-term mitigation appears as more costly compared to postponing mitigation. There are a few IAM studies in which the economic costs of climate change damages are taken into account.[65,66] These studies report that when those costs are taken into account, near-term mitigation appears as more cost-effective than postponing mitigation. Moreover, most IAM pathways typically do not account for the economic impacts of mitigation co-benefits such as improvements air quality, employment or health. The IPCC (2022) states that when both the economic damages of climate change and the co-benefits of mitigation are taken into account, the economic benefits are likely to outweigh the costs of mitigation (p. 85).[12]

5.6.3 Second, IAMs typically do not consider non-linear and catastrophic climate impacts.[67] As defined by the IPCC (2023), a tipping point is 'a critical threshold beyond which a system reorganizes, often abruptly and/or irreversibly' (p. 129).[10] Climate tipping points usually refer

[60] Riahi, K., Bertram, C., Huppmann, D., Rogelj, J., Bosetti, V., Cabardos, A. M., ... & Zakeri, B. (2021). Cost and attainability of meeting stringent climate targets without overshoot. Nature Climate Change, 11(12), 1063-1069.
[61] Stern, N. (2016). Economics: Current climate models are grossly misleading. *Nature*, *530*(7591), 407-409.
[62] Rosen, R. A., & Guenther, E. (2016). The energy policy relevance of the 2014 IPCC Working Group III report on the macro-economics of mitigating climate change. Energy policy, 93, 330-334.
[63] Asefi-Najafabady, S., Villegas-Ortiz, L., & Morgan, J. (2021). The failure of Integrated Assessment Models as a response to 'climate emergency'and ecological breakdown: the Emperor has no clothes. *Globalizations*, *18*(7), 1178-1188.
[64] Köberle, A. C., Vandyck, T., Guivarch, C., Macaluso, N., Bosetti, V., Gambhir, A., ... & Rogelj, J. (2021). The cost of mitigation revisited. *Nature Climate Change*, *11*(12), 1035-1045.
[65] Takakura, J. Y., Fujimori, S., Hanasaki, N., Hasegawa, T., Hirabayashi, Y., Honda, Y., ... & Hijioka, Y. (2019). Dependence of economic impacts of climate change on anthropogenically directed pathways. *Nature Climate Change*, *9*(10), 737-741.
[66] Schultes, A., Piontek, F., Soergel, B., Rogelj, J., Baumstark, L., Kriegler, E., ... & Luderer, G. (2021). Economic damages from on-going climate change imply deeper near-term emission cuts. *Environmental Research Letters*, *16*(10), 104053.
[67] Lontzek, T. S., Cai, Y., Judd, K. L., & Lenton, T. M. (2015). Stochastic integrated assessment of climate tipping points indicates the need for strict climate policy. *Nature Climate Change*, *5*(5), 441-444.

to abrupt, non-linear and irreversible changes in the climate system, such as the loss of Amazon rainforest and the West Antarctic ice sheet.[68] Recently, tipping points have been included in some cost-benefit IAMs (see section 2.1).[69,70,71] These studies all stress that taking into account tipping points would imply the need for more stringent and near-term mitigation compared to scenarios that do not consider tipping points. For example, Yumashev et al. (2019) reported that when economic damages of tipping points are considered, the 1.5°C target appears as more economically attractive compared to the 2°C target. To my knowledge, detailed process IAMs (see section 2.1) have not yet taken into account tipping points. Ignoring tipping points means that IAMs may have been optimistic in their estimates of required emission reductions to meet the Paris Agreement goals. In my view, this implies that the median estimated required emission reduction by IAMs to limit global warming to 1.5°C (45% by 2030) should be considered as the absolute minimum required emission reductions to meet this target. Such an interpretation would also be in line with the precautionary principle underlying the UNFCCC (1992), which states *'Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing such measures,...'* (Article 3.3).

6 Conclusions

The key conclusions of this expert statement are the following:

6.1 IAMs have several analytical qualities that make them well-suited to assess the total required global emissions reductions under the 1.5°C degree target on a global level (section 2). They have also had significant contributions to climate policy (section 4).

6.2 However, the specific assumptions underlying IAM scenarios, including the IAM scenarios in IPCC AR6, are criticized in academic literature and the limitations of these scenarios are acknowledged by the IPCC, most notably their reliance on cost-effectiveness, which disregards interregional equity principles underlying UNFCCC agreements (section 5.3) and their limited representation of real-world feasibility of mitigation measures (5.4).

6.3 The lack of consideration of interregional equity and real-world feasibility imply that IAMs are not well-suited to assess the distribution of CO_2 emission reduction efforts between countries and sectors.

[68] Lenton, T. M., Rockström, J., Gaffney, O., Rahmstorf, S., Richardson, K., Steffen, W., & Schellnhuber, H. J. (2019). Climate tipping points—too risky to bet against. Nature, 575(7784), 592-595.

[69] Cai, Y., Lenton, T. M., & Lontzek, T. S. (2016). Risk of multiple interacting tipping points should encourage rapid CO2 emission reduction. Nature Climate Change, 6(5), 520-525.

[70] Dietz, S., Rising, J., Stoerk, T., & Wagner, G. (2021). Economic impacts of tipping points in the climate system. Proceedings of the National Academy of Sciences, 118(34), e2103081118.

[71] Yumashev, D., Hope, C., Schaefer, K., Riemann-Campe, K., Iglesias-Suarez, F., Jafarov, E., ... & Whiteman, G. (2019). Climate policy implications of nonlinear decline of Arctic land permafrost and other cryosphere elements. *Nature communications, 10*(1), 1-11.

6.4 To my knowledge, no scenario study has yet appeared that takes into account all equity and feasibility considerations when assessing mitigation pathways. Nevertheless, in this report I gave two examples of scenario studies that at least reflected real-world feasibility, sustainability and interregional equity better compared to typical IAM scenarios, which were the study by the IISD (2022)[51] (which considered a selection of the IPCC AR6 scenarios based on feasibility and sustainability of BECCS, fossil CCS and afforestation/reforestation) and the NZE scenario by the IEA (2023)[54] (which considered multiple feasibility considerations of mitigation measures and interregional equity). In my view, the IISD (2022) and IEA (2023) scenarios are therefore more adequate guidelines to assess the regional and sectoral distribution of CO_2 emission reductions compared to the median of IAM scenarios in IPCC AR6.

6.5 As described in section 5.3 and 5.4, scenario studies that take into account the real-world feasibility and interregional equity report higher emission reductions in developed countries compared to the median of C1 scenarios in IPCC AR6. Given that developed countries rely more heavily on oil and gas whereas developing countries rely more strongly on coal, these studies also imply higher emission reductions from oil and gas by 2030 compared to the median of C1 scenarios in IPCC AR6.

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