van de Ven, D.J.; Mittal, S.; Gambhir, A.; Lamboll, R.D.; Doukas, H.; Giarola, S.; Hawkes, A.; Koasidis, K.; Köberle, A.C.; McJeon, H.; Perdana, S.; Peters, G.P.; Rogelj, J.; Sognnaes, I.; Vielle, M.; Nikas, A.2023. A multimodel analysis of post-Glasgow climate targets and feasibility challenges. Nature Climate Change. 13 DOI (
10.1038/s41558-023-01661-0).

A multi-model analysis of post-Glasgow climate targets and feasibility challenges

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Abstract

The COP26 Glasgow process resulted in many countries strengthening their 2030 emissions reduction targets and announcing net-zero pledges for 2050-2070, but it is not clear how this would impact future warming. Here, we use four diverse integrated assessment models (IAMs) to assess CO2 emission trajectories in the near- and long-term based on national policies and pledges, combined with a non-CO2 infilling model and a simple climate model to assess the temperature implications. We also consider the feasibility of national long-term pledges towards net-zero. Whilst near-term pledges alone lead to warming above 2°C, the addition of long-term pledges leads to emissions trajectories compatible with a well-below 2°C future, across all four IAMs. However, whilst IAM heterogeneity translates to diverse decarbonisation pathways towards long-term targets, all modelled pathways indicate several feasibility concerns, relating to the cost of mitigation, as well as to rates and scales of deployed technologies and measures.

Highlights (provisional):

- National long-term climate pledges keep the global peak warming below-2°C (between 1.7 and 1.8°C)
- Emission intensity reduction needs to accelerate post-2030 to achieve long-term ambitions if NDCs not strengthened
- Globally implemented policies are inconsistent with 2030 NDCs
- Feasibility concerns of modelled long-term pledges are found for all models and regions, yet on different angles of feasibility
- Dedicated policy required to overcome mapped feasibility bottlenecks for achieving long-term targets consistent with the Paris Agreement
- Focus on short- and long-term implementation of announced pledges crucial to avoid exceeding 2°C of global warming.

In the Paris Agreement, adopted in 2015, countries agreed to hold global mean temperature rise to well-below-2°C while pursuing to limit it to 1.5°C. The scientific community has since focussed its efforts on understanding what it would take for the world to meet this target[1]. Modellers have looked at requirements to meet the most stringent 1.5°C ambition[2], quantifying the necessary transformations[3,4] and the consequences of living in a 2°C rather than a 1.5°C world[5]. Initial climate pledges in the context of Paris negotiations were soon found inadequate[6] but, despite the slower-than-necessary pace[7,8], countries have kept ramping up their ambition since. Several studies have quantified the actual impact of international policy efforts[9–11], showcasing that 'business-as-usual' scenarios that are loosely defined and/or miss this impact of hitherto efforts are not helpful[12,13], increasing pressure for better, more realistic analysis of where the world is heading[14]. A growing body of literature[15–17], thus, shed light on what policies currently in place as well as official 2030 Nationally Determined Contributions (NDCs) would yield, establishing their inadequacy to limit warming to 2°C[18,19].

Although the critical climate talks of the 26th Conference of the Parties (COP26)—a milestone for ratcheting ambition—were delayed by a year due to COVID-19, parties followed up on their commitments; by the time COP26 was completed in Glasgow in November 2021, more than 120 countries had upgraded their 2030 targets[20] and major emitters representing over 70% of global CO_2 emissions had announced and/or adopted net-zero commitments[21]. A handful of studies attempted to quickly assess the outcome of these new promises[22–26], showing that—if fully implemented—global climate ambition could hold global temperature rise to just-below-2°C by 2100. More efforts to comprehend the effect of the new generation of NDCs and long-term targets (LTTs) followed[27,28]. Nonetheless, each of these studies was based on a single model and, despite stagnation of new such bold promises largely due to the current energy crisis[29], a multi-model assessment of global climate pledges remains critical. Our study contributes to this research gap, aiming to enhance robustness and confidence in our knowledge of possible global warming outcomes, by exploiting a diverse ensemble of integrated assessment models (IAMs) and breaking down the climate action gap in an implementation gap (temperature difference between current policies and NDCs), a long-term ratchet gap (temperature difference between NDCs followed or not by LTTs), and an ambition gap (difference between temperature achieved by LTTs and the 1.5ºC goal) (see Figure 1 and 'Climate action gap definition' in Methods).

Model diversity also implies a plurality of modelling paradigms, theories, solution mechanisms, and thus pathways that each model yields[30]. Given the political commitment to 1.5°C—which was further strengthened in the Glasgow Climate Pact[1]—and the ambition reflected in announced net-zero pledges, special emphasis is increasingly placed on thresholds or boundaries that modelled pathways must stay within to be considered feasible[31]. According to the 6th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR6), feasibility refers to the potential for a mitigation (or adaptation) option to be implemented, based on diverse context-dependent factors[32]—including institutional, financial, and political[33–35]. Conversely, from a modelling perspective, feasibility refers to quantifiable geophysical, environmental-ecological, technological, economic, and even sociocultural factors[36]. Feasibility assessments hitherto referred to challenges at the global level[37,38] and/or have been used to explicitly assess 1.5°C-compliant pathways[39], without touching upon regional feasibility concerns of decarbonisation pathways required to achieve announced pledges. Our study builds on the multidimensional feasibility assessment framework established by Brutschin et al. (2021)[37], to identify where and when the largest bottlenecks to achieving climate targets can be found, from a socioeconomic, technological, and physical feasibility perspective (See Figure 1 and 'Feasibility assessment' in Methods). However, a key novelty of our study lies in the expansion of the regional disaggregation of this framework, allowing to assess to what extent and from which perspective countries' policy targets, NDCs, and LTTs are feasible.

Global action gap

We use three scenarios, each corresponding to a different level of climate action or stated ambition, as announced by June 2022 (Figure 1): a scenario with current emission reduction policies until 2030, with post-2030 extrapolation maintaining 2020-2030 emission intensity tendencies (EI; see 'Scenario Protocol' in Methods); a scenario with current NDC targets for 2030, with the same EI extrapolation; and a scenario with NDC targets until 2030 followed by LTTs.

To compare emissions between scenarios we focus on global CO_2 emissions from energy and industrial processes to 2050 as all our IAMs represent these emissions sources as a minimum, while we include non-CO_2 emissions and short-lived climate forcers in our temperature assessment (see below). When including all relevant national and regional energy and climate policies on top of socio- and techno-economic baseline assumptions, we find that CO_2 emissions will stabilise or start declining in the current decade, reaching 33-38 Gt by 2030 (Figure 2). If policy effort is sufficiently strengthened to reach stated NDC targets, we find across models that emissions are reduced towards 2030, reaching 30-33 Gt. If all countries continue their declining trend in emission intensity of GDP beyond 2030, global emissions will achieve levels of around 24-30 Gt and 19-23 by 2050—for current policies and NDCs, respectively. However, if countries accelerate action post-2030 to meet their long-term emission targets, we find 2050 emissions in the range of 10-13 Gt.

Model spread is largest for current policies, since models run largely in forecasting mode, simulating the impact of policies relative to a model-dependent no-policy baseline. Despite harmonisation of many input assumptions to reduce unwanted response heterogeneity (see 'Scenario Protocol' in Methods), no-policy baselines tend to differ strongly, driven by inherent model characteristics and remaining unharmonised inputs[18]. Therefore, despite the converging effect of modelling a common set of current energy and climate policies, model variation still tends to be large in such exercises[14,40] (Table 1). Model spread for emissions significantly decreases when emission targets from NDCs and LTTs are used as absolute constraints. The remaining emission spread can be explained by a mix of factors, such as model regions overperforming their targets, differences in regional aggregation, and the CO_2 vs non-CO_2 share in emission reductions. While total emissions outcomes between models converge when applying constraints, the distribution of emissions over the different sectors diverge between the models, reflecting the heterogeneity of mitigation pathways preferred by each model (see Extended Data Figure 1).

While temperature outcomes depend on all CO_2 emissions (energy, industrial processes, and land use), the remaining Kyoto gases (CH_4, N_2O, and fluorinated gases), and short-lived climate forcers (SO_2, black and organic carbon, etc), most of our models only cover a subset of those (Table 1). Therefore, we estimate the temperature implications of our scenarios after infilling missing greenhouse gases (GHGs) and climate forcers, harmonising the emission data, and running the emission outcomes through the simple climate model FaIR (see Temperature Assessment section in Methods). We find that current ambition levels signalled through implemented energy and climate policies will increase global temperatures to 2.1-2.4°C above pre-industrial levels by 2100, depending on the model (1.9 – 2.7°C when including climate uncertainty at the 25-75% interval), while ambition levels stated in present NDCs slightly limit this increase to 2.0-2.2°C (1.7-2.5°C for 25-75% interval). In both cases, warming will continue after 2100, as global CO_2 emissions will not have yet reached net-zero levels. If countries also comply with their stated LTTs after meeting their current NDC pledges in 2030, temperature increase will be further limited and stabilise around 1.7-1.8°C (1.5-

2.0°C for 25-75% interval), which is arguably in line with a "well-below-2°C" future[41]. Depending on the model applied, this translates to an implementation gap of 0.1-0.4°C additional warming on the one hand, and a long-term ratchet gap equivalent to another 0.2-0.5°C of warming on the other. The remaining global ambition gap compared to the Paris target of keeping global temperature increase to 1.5°C would be around 0.2-0.3°C for all models. For 3 out of 4 models (GEMINI, MUSE, and TIAM), the long-term ratchet gap contributes most to the entire climate action gap. This confirms previous assessments showing that mitigation in current NDCs is not aligned with long-term targets for most countries[24,27]. For GCAM, the implementation gap contributes most to the entire gap, instead.

Disaggregating the emission results for the six largest emitters (Figure 4) shows where the different gaps are more relevant. The implementation gap is measured to be largest (in relative terms) for the USA and Japan, which have relatively ambitious NDCs but their policies are lagging behind. For countries with relatively less ambitious NDCs, like China, India, and Russia, the implementation gap is smaller or non-existent, as existing policies overachieve NDC targets in several cases. In the EU, the implementation gap is relatively small due to ambitious policies. The long-term ratchet gap is significant for all cases, meaning that, with current NDC targets, all six regions require a significant boost in post-2030 climate action for their net-zero targets to be achievable. However, differences between models are non-negligible, as GCAM shows an implementation gap in all countries except Russia, while GEMINI only for the USA. Driven largely by announced emissions targets, pathways towards long-term targets are relatively similar between the models, except India and Russia, due to different modelled or assumed contributions from non-CO_2 emissions and natural sinks towards net-zero targets. We have not assessed the ambition gap at the country level, as that would require an assessment of fairness and equity[42].

Scenario feasibility

The feasibility of the modelled scenarios based on national policies and targets is measured by comparing specific scenario outcomes with pre-determined thresholds (see Supplementary section 2). Surpassing a threshold indicates that the feasibility of achievement in that dimension might become concerning. Global results show that feasibility concerns vary strongly between models, between scenarios, and over time (Figure 3a). Logically, deeper mitigation efforts imply larger feasibility concerns, as they drive models further away from their emissions-unconstrained baselines. Achieving stated long-term targets among all countries—the only option of keeping temperature increase well-below-2°C (Figure 2)—implies that regional feasibility thresholds must be passed three-to-six times (global weighted average and with median thresholds), depending on the model and aggregated over the different feasibility dimensions. The feasibility metrics are only based on mitigation and do not consider the adaptation challenges that are driven by lack of mitigation. In fact, the feasibility of adequate adaptation to make up for lack of mitigation may be significantly more concerning—i.e., in terms of costs, pace of investment scale-up, and land and freshwater availability[43,44]—but this is outside the scope of this study. These feasibility concerns can, therefore, be best understood as key aspects requiring attention for successful implementation of the ambitious mitigation policies.

Since the models differ significantly in structure, resulting in a wide variety of mitigation pathways, this also translates to large variations in the level and timing of feasibility concerns between the four models (Table 1), with GEMINI showing the lowest and MUSE the highest concerns. However, the distribution of feasibility concerns over the different dimensions and over time are crucial for the interpretation. For example, the high overall concern for MUSE is largely driven by high carbon prices and demand reduction pathways. In contrast, these dimensions are hardly of concern for GCAM and TIAM, where the pace of technology deployment and—in the case of GCAM—reliance on bioenergy and CCS are the main sources of feasibility concern. When evaluating feasibility concerns over time, all three TIAM scenarios stand out for showing most near-term concerns, predominantly related to the high pace of wind and solar energy deployment to deliver on 2030 targets. In GCAM, feasibility concerns are relatively small in the run-up to 2030, but arise in later periods, largely driven by increasing reliance on bioenergy with carbon capture and storage (BECCS). The latter is concerning from three different feasibility perspectives: pace of technology deployment, availability of sustainable bioenergy resources, and geological carbon storage capacity.

Mitigation scenarios in this study are entirely driven by country-specific climate policies and ambitions, hence we also specify an overview of measured feasibility concerns for the six largest emitters, averaged over 2020-2050 (Figure 4). While again large differences between models exist, overall, we see relatively low concerns in China and Russia, and high concerns in the USA, the EU, and Japan. These differences are likely driven by more ambitious targets in the latter group, which—despite being already in an emission reduction phase for at least a decade—still confront high feasibility constraints to meet their near- and longer-term targets. Specific feasibility issues that stand out include energy demand reductions in the USA (GEMINI), carbon pricing in the EU (MUSE), and bioenergy and carbon storage potentials for Japan (GCAM). Feasibility concerns about the pace of technology deployment play a relatively small role in China, the USA, and the EU, as opposed to India, Russia, and Japan.

The interpretation of the measured feasibility concerns can be subjective. The pre-determined thresholds are not set in stone, and often large ranges for such thresholds exist in literature[37,38], while threshold levels strongly affect measured feasibility concerns—as showcased in a sensitivity analysis illustrating the impact of threshold uncertainty on feasibility concern values (Figure 3b). Experts in different fields may have very different views on what is feasible or not. At the same time, our definition of feasibility is defined by 10 indicators, as constrained by our modelling capacity (see Table 2 and Feasibility Assessment section in Methods); including other indicators in the analysis might have highlighted different dimensions and affected overall (aggregate) feasibility levels. Also, country-specific features, such as country size, stage of development, economic structure, or access to international financial markets, would influence the threshold level. While some of these features are weighted in the feasibility assessment (e.g., the thresholds for carbon pricing depend on GDP per capita levels), not all can be considered (e.g., economic structure). Moreover, our feasibility assessment only applies to the underlying socioeconomic "storyline" provided in the scenario protocol (see 'Scenario Protocol' in Methods). Emissions associated with our pathways, largely constrained by 2030 NDCs and net-zero targets, are not subject to wide variation across storylines, as the latter would be without emissions constraints[45] (noting that, for India and China, the emissions-intensity-based NDCs will vary according to their projected economic growth). However, existing analysis shows that key feasibility-related indicators of 1.5°C pathways—including average annual CO_2 sequestration from negative emissions, scale-up of low-carbon primary energy share, final energy demand, and carbon prices—show considerable variation across storylines (in this case the shared socioeconomic pathways[46]), even for a given model[2]. Such analysis also demonstrates that inter-model variation is comparably wide in many cases, so a multi-model assessment (even with one storyline) still usefully highlights the potential range of each feasibility indicator.

A final consideration around feasibility is that the thresholds are not immutable laws—indeed, some historical cases prove that the chosen thresholds can be overcome. An example is the surge of gas-fired power in the Netherlands and nuclear power in France, which respectively surged from 5% to 80% and 25% to 75% of the power mix in one decade, surpassing the applied feasibility threshold in this study over 10-fold. Since such historical examples of fast transitions are typically driven by public policy and support[47], the feasibility analysis can also be interpreted as a mapping exercise of where policy support is strongly needed to overcome existing constraints, which is crucial for achieving stated climate targets as all models and scenarios in this study surpass several feasibility thresholds. Nevertheless, as the results show, this mapping strongly depends on the applied model: deep structural differences between models lead to a wide variety of pathways reaching the same climate targets and, hence, different policy interventions are necessary from different modelling perspectives to make these pathways feasible.

Discussion

Our results suggest that, if announced national near- (2030) and longer-term (2050-2070) emission reduction ambitions throughout the world are achieved, global peak temperature increase will stay below 2°C with ~75% certainty. However, if climate action is not strengthened post-2030, long-term ambitions will not be achievable (long-term ratchet gap), and global temperature increase will be around or above 2°C by 2100. All applied models agree that—with the current pace of policy implementation—temperature increase will not exceed 2.5°C over the course of the century but will still have a rising trend thereafter. These results clearly show that climate action and ambitions have notably improved since 2020, when the same set of models and scenario structure projected 2030 emissions to be on average 3 Gt CO_2 higher (see Extended Data Figure 2) and mean global temperature 0.2-0.3°C warmer by 2100[18]. This improvement, alongside our finding that global emissions are set to peak in the current decade with current NDCs, is in line with earlier post-COP26 assessments[22–24,27,28]. The latter assessments, however, also found increasing emissions for current policy scenarios throughout and after the 2020s[22,27,28], whereas all models in our study find reduction or stabilisation of emissions with current policies within this decade. Furthermore, using a diverse set of different IAMs and thus covering a large part of structural uncertainty while reducing undesired model response heterogeneity, our study offers a more robust assessment of emissions and warming implications of post-Glasgow pledges and action, compared to these earlier single-model assessments.

Accounting for post-2030 extrapolations of current policies and NDCs, this study shows significantly lower emissions and end-of-century temperatures than other studies; additionally, our multi-model LTT projections are slightly more optimistic (by ~0.1°C). An important reason for this difference likely lies in the applied extrapolation method: in contrast to a continued trend in emission intensities used in this study, other studies applied a carbon price equivalent to 2030 action and increasing over time with GDP levels[23,27,28], a method leading to more conservative emission reductions in most models[18]. There is no straightforward answer on which policy extrapolation method is better: while continuing a trend in emission reductions may falsely bank on an emission reduction trend that might not be equally attainable in the future, relying on extrapolated carbon prices may put too much faith in highly uncertain future model assumptions, especially considering that, e.g., the decline in costs of low-carbon technologies have traditionally been underestimated in such assumptions[12]. Another important difference with several other model studies in the literature is that current policies are modelled explicitly (i.e., not proxied via carbon prices until 2030, see Supplementary Data 1) and on top of an up-to-date, harmonised set of socio- and techno-economic assumptions. This contributes to the relatively optimistic assessment of 2030 emissions in the study, as it endogenously assumes ratcheting of emission reduction targets (by overperforming on these targets), where these are not ambitious.

Our scenario structure reflects three levels of ambition, where for each separate model region emissions are equal or lower with each subsequent level of ambition. Similarly, uncertainty to reach the modelled emission reduction also increases with each subsequent level of ambition. Hence, despite aggregated national ambitions being in line with a well-below-2°C temperature future, the likelihood of all these national ambitions being achieved should not be overestimated. For each individual country that fails to meet its targets, the probability of higher temperature levels increases. Our feasibility analysis shows that, for most countries, it is far from straightforward to achieve their stated near- and long-term ambitions with the anticipated future demand patterns and technologies. The feasibility analysis in this study shows that there is no “free lunch” in terms of feasibility of mitigation pathways: while different model structures imply heterogenous pathways to decarbonise economies in line with proposed pledges, each of the pathways compatible with a well-below-2°C temperature future faces significant feasibility challenges, either in socioeconomic, technology scale up, physical or sustainability dimensions. However, such feasibility challenges should not be interpreted as hard barriers to meet pledged mitigation targets, but rather as areas where additional policy support or breakthroughs in technology or consumer behaviour[48] may be needed to overcome such challenges.

Our results show that aggregating all national near- and long-term emission reduction targets is still insufficient to limit global temperature increase to 1.5°C (long-term ambition gap), which is the highest ambition of the Paris Agreement. Even if the most ambitious scenarios in this study are achieved, the temperature increase may still cause significantly notable and damaging climate impacts[49], and be sufficiently strong to activate several climate tipping elements, such as the collapse of the Greenland and West Antarctic ice sheet and the die-off of low-latitude coral reefs[50,51]. Therefore, even if ambitions have significantly improved in the run-up to and shortly after COP26, cumulative emissions until 2050 must be reduced significantly more to avoid overshooting the 1.5°C target, or substantive negative emissions should be achieved after reaching LTTs to reach 1.5°C by 2100 with a high overshoot (see Extended Data Figure 3). Nevertheless, the results of this study show that, while the focus on further ambition ratcheting should not be lost[8], a high focus on the short- and long-run implementation of the existing set of ambitions is significantly more important to avoid a climate disaster.

Acknowledgements

D.V., S.M., A.G., H.D., S.G., A.H., K.K., A.K., S.P., G.P., J.R., I.S., M.V. and A.N. acknowledge support from the H2020 European Commission Project PARIS REINFORCE (grant no. 820846). R.L. acknowledges support from the H2020 European Commission Project PROVIDE (grant no. 101003687). D.V., S.M., A.G., H.D., S.G., A.H., K.K., G.P., I.S. and A.N. also acknowledge support from the Horizon Europe R&I programme project IAM COMPACT (grant no. 101056306).

Author contribution statement

D.V., S.M., A.G., G.P., J.R. and A.N. coordinated the study design and scenario protocol; all authors were involved in the model analysis, with notable contributions from D.V., H.M. (GCAM), S.P., M.V. (GEMINI), S.G., A.H. (MUSE), S.M., A.G., A.K. (TIAM) and R.L. (Silicone and FaIR). D.V., S.M., A.G., G.P., I.S. and A.N. compiled and analysed the results and created the figures, with feedback from all other authors. D.V. coordinated the conception and writing of the paper with notable contributions from A.N., K.K., S.M. and A.G. and feedback and contributions from all other authors.

Competing interests statement

The authors declare no competing interests.

Table 1: Model key characteristics and mapping of characteristics to major feasibility concerns

	GCAM-PR	**GEMINI-E3**	**MUSE**	**TIAM-Grantham**
Model type	Partial equilibrium	General equilibrium	Agent-based energy-system	Partial equilibrium
Solution dynamic	Recursive-dynamic	Recursive-dynamic	Recursive-dynamic	Inter-temporal optimisation (perfect foresight)
Technology choice	Logit choice	Nested CES function	Agent decision goals and strategies	Winner takes all
GHG emission coverage (reported)	Fossil CO_2, CH_4, N_2O, Land-use CO_2, F-gases	Fossil CO_2, CH_4, N_2O, F-gases	Fossil CO_2	Fossil CO_2
Model regions	32	11	20	15
Time horizon	2100	2050	2100	2100
Unconstrained baseline CO_2 [1]	High	High	Low	Medium
Impact of current policies [1]	Medium	High	Low	High
Major feasibility concerns with LTTs[2]**:**				
Timing and indicator	Long-term bioenergy and carbon storage	Long-term energy demand reduction	Near and long-term carbon pricing	Near term technology scale-up
Region(s)	India, Japan	USA	EU, Japan	EU, India, Japan
Explanation based on model structure	Due to the endogenous representation of the land sector, no hard limits are set to bioenergy supply. High energy prices stimulate bio-energy output from land beyond sustainable limits.	As a general equilibrium model, the entire economy is simulated, including economic feedbacks to end-use sectors. High energy prices therefore lead to relatively high demand reduction	Due to high inertia by modelled agents and technology stickiness, high carbon prices are required to switch to low carbon technologies and/or reduce demand.	As an inter-temporal perfect foresight model, agents have perfect foresight towards the future, driving the near-term investment in renewable technologies.

[1] For baseline CO_2, High > 40 $GtCO_2$, low < 30 $GtCO_2$, Medium = 30-40 $GtCO_2$ by 2050. For impact from current policies, High > 6 $GtCO_2$, Low < 3 $GtCO_2$, Medium = 3-6 $GtCO_2$ reduction to baseline in 2030.

[2] Major feasibility concerns are identified separately per model, and not by comparing feasibility concerns between the different models.

Table 2: List of applied feasibility indicators with relevant threshold data (more details in Methods)

Feasibility category	**Feasibility indicator**	**Threshold unit**	**Threshold value**	**Regional variability**	**Temporal variability**	**Regional weight variable [1]**
Socio-economic	Carbon pricing burden	US$2010 / t CO2	$50 (global average in 2020)	Regional threshold value marked by regional GDP PPP relative to global average GDP PPP.	Global average threshold value increases with 5% by annum.	Fossil CO_2 emissions in 2020
	Industry energy demand	% decadal decrease in energy end-use consumption per capita	10 %	N/A (threshold unit is already relative)	N/A [3]	Population size
	Buildings energy demand					
	Transport energy demand					
Technology scale-up	Power sector technologies	% decadal increase of technology share in total output (power) or energy carrier mix (end use sectors)	5 % for thermal and 10% for non-thermal power technologies	Feasibility concern level by region scaled by decadal growth in power production	N/A [3]	Power production
	Industry end-use technologies		10 % for all end-use energy carriers	N/A (scale effect ignored due to impact of energy carrier switching)	N/A [3]	Final energy consumption by sector
	Buildings end-use technologies					
	Transport end-use technologies					
Physical / Sustainable	Bioenergy production	EJ bioenergy consumption	155 EJ (globally by 2050)	Threshold value sub-divided by regions [2]	Threshold value increases linearly from estimated 2020 consumption (57 EJ) to 2050	Bioenergy consumption
	Geological carbon storage	Gt carbon storage potential	214 Gt CO_2 of cumulative storage (globally by 2050)	Threshold value sub-divided by regions [2]	Threshold value increases linearly from zero in 2010 to 2050	Cumulative carbon storage

[1] Weight variable used for calculation of global average through regionally identified feasibility concerns (Figure 3)

[2] In order to reflect potential trade possibilities for bioenergy and carbon storage (e.g. near borders), a multiplier is applied to the regionally identified feasibility concern levels, based on global bioenergy and carbon storage relative to the global threshold level (e.g. below 1 reflects trade possibilities to stay within global feasibility limit).

[3] Threshold unit is a relative value (% change over one decade) and applying temporal variability to the threshold level is therefore not meaningful.

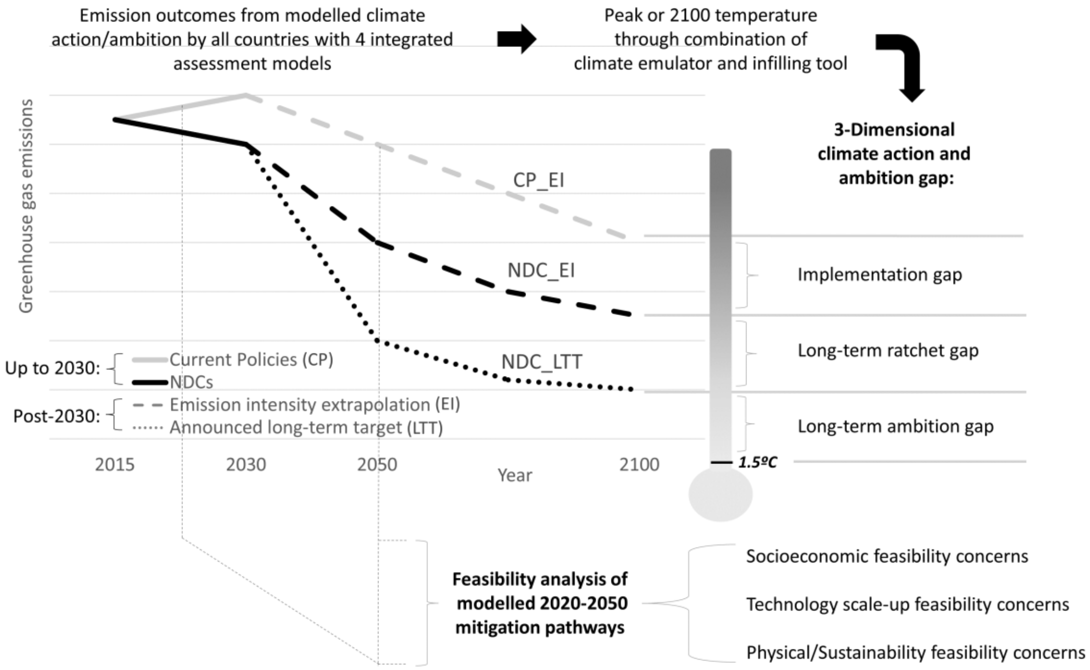


Figure 1: Global overview of study design (fictional data points for graphical representation). The 4 IAMs applied are GCAM-PR, GEMINI-E3, MUSE and TIAM-Grantham. The climate emulator used is FaIR, using SILICONE as infilling tool. See Methods for more details.

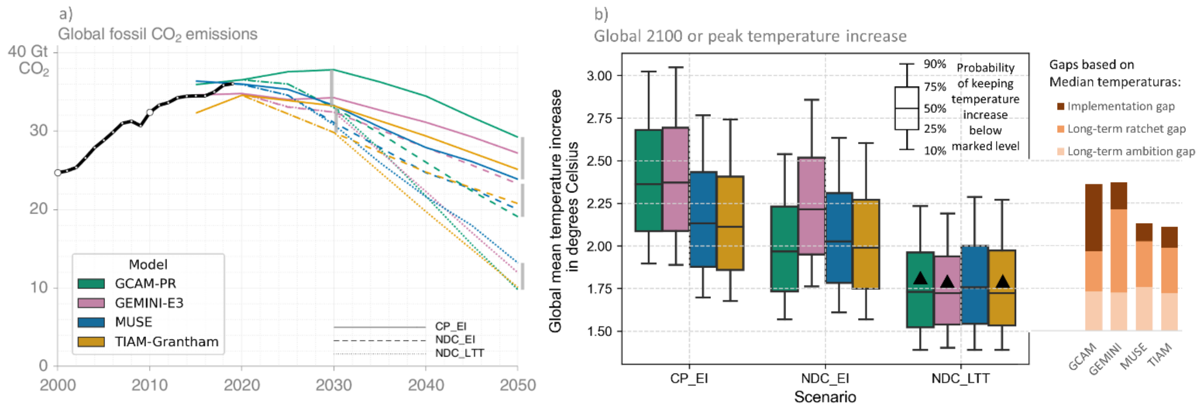


Figure 2: Global CO_2 emissions from fossil fuel combustion (a), as well as temperature outcomes across the four models and three scenarios used in this study, and the distribution of the climate action gap based on median temperatures (b). Historical emissions (black solid line) are taken from CEDS database[52]. Temperature box plots for all scenarios and models are derived from 2237 runs using the simple climate model FaIR (see Methods). Triangles in temperature box plots mark peak temperatures achieved before 2100. In scenarios without triangle, 2100 temperatures are represented which are still on an increasing trend.

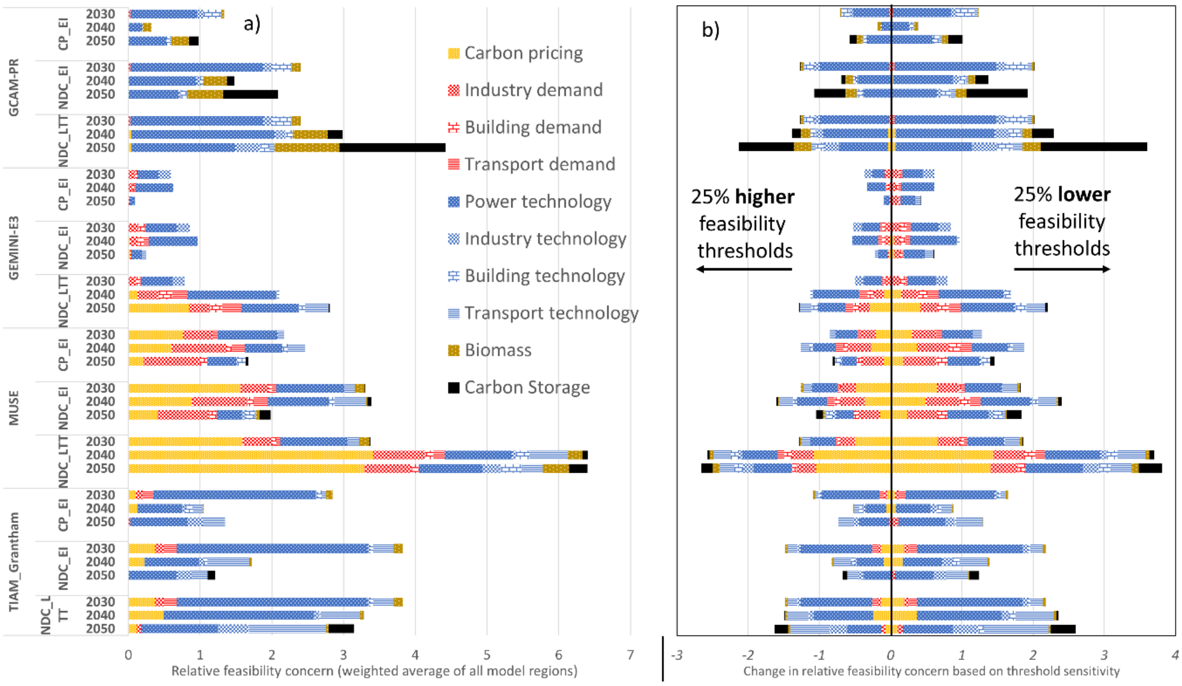


Figure 3: Globally averaged feasibility concerns of all scenarios by feasibility indicator. Panel a) shows the concerns for the set of chosen feasibility thresholds in this study (see Methods), panel b) shows the sensitivity of feasibility concerns to the chosen threshold level. For all indicators, a concern value of 1 represents that the specific threshold for that indicator is surpassed by 100% in that specific model region and period. Similarly, score of 0.5 and 1.5 mean surpassing the thresholds by respectively 50% and 150%. As long as the threshold is not passed, even if it comes close, the feasibility concern is measured as zero. Similarly for all indicators, the global value is built up as a weighted average of the independent values in all model regions. See Table 2, Methods and Supplementary Section 2 for further details.

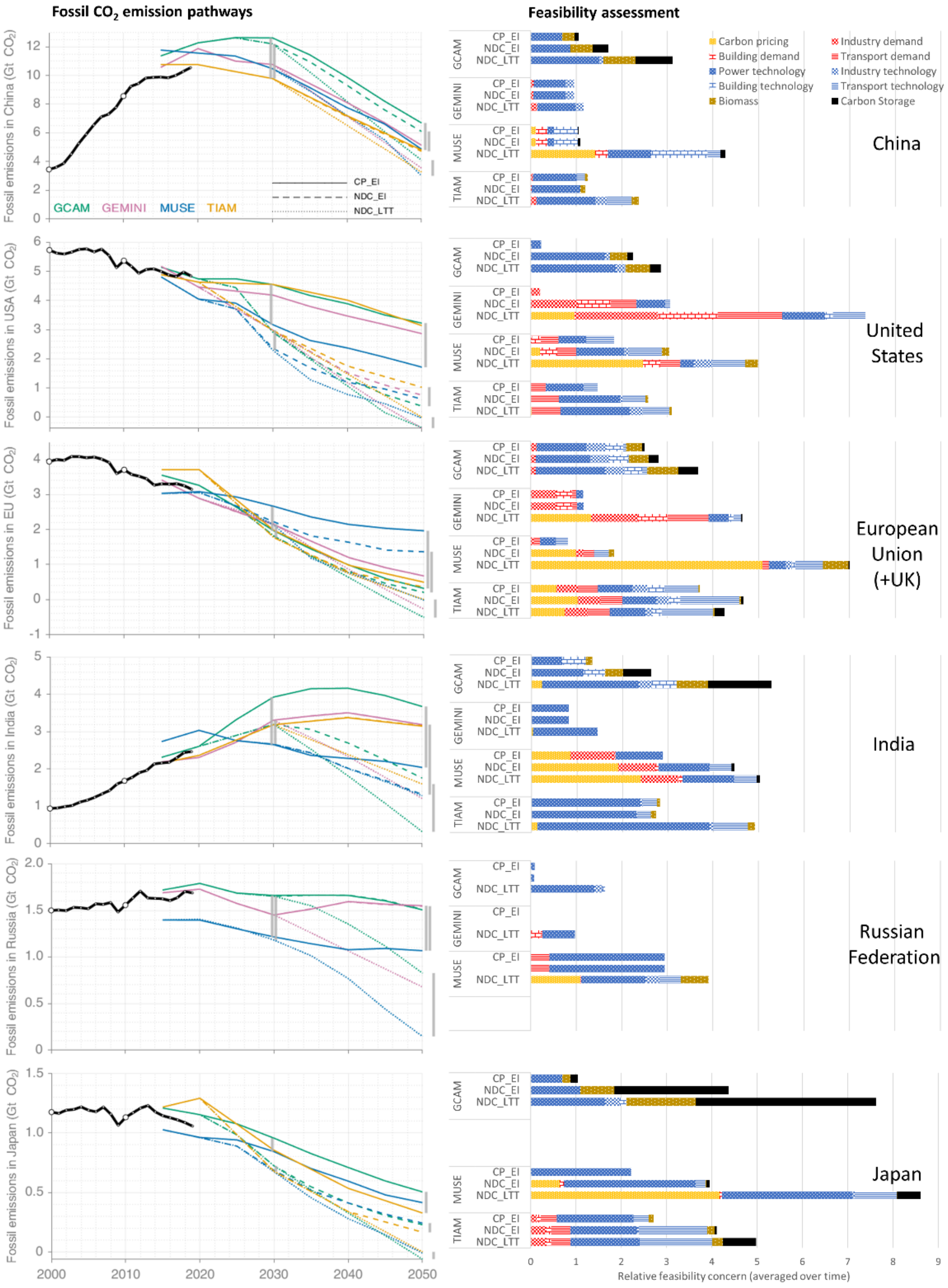


Figure 4: Emissions pathways and feasibility analysis for six largest emitters, across all four 4 models and 3 scenarios in this study. Historical emissions (black solid lines) are taken from CEDS database[52]. See Figure 3 and Methods for more details on feasibility measurement.

References

1. Schleussner, C.-F., Ganti, G., Rogelj, J. & Gidden, M. J. An emission pathway classification reflecting the Paris Agreement climate objectives. *Commun. Earth Environ.* **3**, 135 (2022).

2. Rogelj, J. *et al.* Scenarios towards limiting global mean temperature increase below 1.5 °c. *Nat. Clim. Chang.* **8**, 325–332 (2018).

3. Gambhir, A., Rogelj, J., Luderer, G., Few, S. & Napp, T. Energy system changes in 1.5 C, well below 2 C and 2 C scenarios. *Energy Strateg. Rev.* **23**, 69–80 (2019).

4. Rogelj, J. *et al.* Energy system transformations for limiting end-of-century warming to below 1.5 °C. *Nat. Clim. Chang.* **5**, 519–527 (2015).

5. IPCC. *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,*. (2018).

6. Rogelj, J. *et al.* Paris Agreement climate proposals need a boost to keep warming well below 2 °c. *Nature* **534**, 631–639 (2016).

7. Grant, N. The Paris Agreement's ratcheting mechanism needs strengthening 4-fold to keep 1.5° C alive. *Joule* **6**, 703–708 (2022).

8. Iyer, G. *et al.* Ratcheting of climate pledges needed to limit peak global warming. (2022) doi:10.1038/s41558-022-01508-0.

9. Le Quéré, C. *et al.* Drivers of declining CO 2 emissions in 18 developed economies. *Nat. Clim. Chang.* **9**, 213–218 (2019).

10. Eskander, S. M. S. U. & Fankhauser, S. Reduction in greenhouse gas emissions from national climate legislation. *Nat. Clim. Chang.* **10**, 750–756 (2020).

11. Maamoun, N. The Kyoto protocol: Empirical evidence of a hidden success. *J. Environ. Econ. Manage.* **95**, 227–256 (2019).

12. Grant, N., Hawkes, A., Napp, T. & Gambhir, A. The appropriate use of reference scenarios in mitigation analysis. *Nat. Clim. Chang.* **10**, 1–6 (2020).

13. Hausfather, Z. & Peters, G. P. Emissions – the 'business as usual' story is misleading. *Nature* **577**, 618–620 (2020).

14. Roelfsema, M. *et al.* Taking stock of national climate policies to evaluate implementation of the Paris Agreement. *Nat. Commun.* **11**, 2096 (2020).

15. Vandyck, T., Keramidas, K., Saveyn, B., Kitous, A. & Vrontisi, Z. A global stocktake of the Paris pledges: Implications for energy systems and economy. *Glob. Environ. Chang.* **41**, 46–63 (2016).

16. Vrontisi, Z. *et al.* Enhancing global climate policy ambition towards a 1.5 °C stabilization: a short-term multi-model assessment. *Environ. Res. Lett.* **13**, 44039 (2018).

17. McCollum, D. L. *et al.* Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nat. Energy* **3**, 589–599 (2018).

18. Sognnaes, I. *et al.* A multi-model analysis of long-term emissions and warming implications of current mitigation efforts. *Nat. Clim. Chang.* **11**, 1055–1062 (2021).

19. United Nations Environmental Programme. *Emissions Gap Report 2022: The Closing Window*

— *Climate crisis calls*. https://www.unep.org/resources/emissions-gap-report-2022 (2022).

20. UNFCCC. *Nationally determined contributions under the Paris Agreement: Revised synthesis report by the secretariat*. https://unfccc.int/sites/default/files/resource/cma2021_08r01_E.pdf (2021).

21. Höhne, N. *et al.* Wave of net zero emission targets opens window to meeting the Paris Agreement. *Nat. Clim. Chang.* **11**, 820–822 (2021).

22. Ou, Y. *et al.* Can updated climate pledges limit warming well below 2°C? *Science (80-.).* **374**, 693–695 (2021).

23. IEA. COP26 climate pledges could help limit global warming to 1.8 °C, but implementing them will be the key. (2021).

24. Meinshausen, M. *et al.* Realization of Paris Agreement pledges may limit warming just below 2° C. *Nature* **604**, 304–309 (2022).

25. Wiltshire, A. *et al.* Post COP26: does the 1.5°C climate target remain alive? *Weather* (2022) doi:10.1002/wea.4331.

26. den Elzen, M. G. J. *et al.* Updated nationally determined contributions collectively raise ambition levels but need strengthening further to keep Paris goals within reach. *Mitig. Adapt. Strateg. Glob. Chang.* **27**, 33 (2022).

27. Garaffa, R. *et al.* Global and Regional Energy and Employment Transition Implied by Climate Policy Pledges. *SSRN Electron. J.* (2022) doi:10.2139/ssrn.4141955.

28. Aleluia Reis, L. & Tavoni, M. Glasgow to Paris—The impact of the Glasgow commitments for the Paris climate agreement. *iScience* **26**, 105933 (2023).

29. Kemfert, C., Präger, F., Braunger, I., Hoffart, F. M. & Brauers, H. The expansion of natural gas infrastructure puts energy transitions at risk. *Nat. Energy* **7**, 582–587 (2022).

30. Nikas, A. *et al.* Perspective of comprehensive and comprehensible multi-model energy and climate science in Europe. *Energy* **215**, (2021).

31. Gambhir, A., Butnar, I., Li, P.-H., Smith, P. & Strachan, N. A review of criticisms of integrated assessment models and proposed approaches to address these, through the lens of BECCS. *Energies* **12**, 1747 (2019).

32. Skea, J., Shukla, P. R., Reisinger, A., Slade, R. & Pathak, M. *Summary for policymakers*. *IPCC (2022) Climate Change* (2022).

33. Patterson, J. J. *et al.* Political feasibility of 1.5 C societal transformations: the role of social justice. *Curr. Opin. Environ. Sustain.* **31**, 1–9 (2018).

34. Bednar, J., Obersteiner, M. & Wagner, F. On the financial viability of negative emissions. *Nat. Commun.* **10**, 1–4 (2019).

35. Jewell, J. & Cherp, A. On the political feasibility of climate change mitigation pathways: is it too late to keep warming below 1.5° C? *Wiley Interdiscip. Rev. Clim. Chang.* **11**, e621 (2020).

36. Kriegler, E. *et al.* Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. *Technol. Forecast. Soc. Change* **90**, 24–44 (2015).

37. Brutschin, E. *et al.* A multidimensional feasibility evaluation of low-carbon scenarios. *Environ. Res. Lett.* **16**, 064069 (2021).

38. Gambhir, A. *et al.* Assessing the Feasibility of Global Long-Term Mitigation Scenarios. *Energies* **10**, 89 (2017).

39. Warszawski, L. *et al.* All options, not silver bullets, needed to limit global warming to 1.5 C: A scenario appraisal. *Environ. Res. Lett.* **16**, 64037 (2021).

40. Giarola, S. *et al.* Challenges in the harmonisation of global integrated assessment models: A comprehensive methodology to reduce model response heterogeneity. *Sci. Total Environ.* **783**, 146861 (2021).

41. Rogelj, J. *et al.* Mitigation pathways compatible with 1.5°C in the context of sustainable development. in *Special Report on the impacts of global warming of 1.5 °C* (Intergovernmental Panel on Climate Change, 2018).

42. Robiou du Pont, Y. *et al.* Equitable mitigation to achieve the Paris Agreement goals. *Nat. Clim. Chang.* **7**, 38 (2016).

43. Pörtner, H.-O. *et al.* Climate change 2022: Impacts, adaptation and vulnerability. *IPCC Sixth Assess. Rep.* (2022).

44. Markandya, A., Galarraga, I. & Murieta, E. S. De. *Routledge handbook of the economics of climate change adaptation*. (2014).

45. Marangoni, G. *et al.* Sensitivity of projected long-term CO2 emissions across the Shared Socioeconomic Pathways. *Nat. Clim. Chang.* **7**, 113–117 (2017).

46. O'Neill, B. C. *et al.* A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Clim. Change* **122**, 387–400 (2014).

47. Fouquet, R. Historical energy transitions: Speed, prices and system transformation. *Energy Res. Soc. Sci.* **22**, 7–12 (2016).

48. Perdana, S. *et al.* Expert perceptions of game-changing innovations towards net zero. *Energy Strateg. Rev.* **45**, 101022 (2023).

49. Hoegh-Guldberg, O., Jacob, D., Taylor, M., Bindi, S. & Zhou, G. Impacts of 1.5°C Global Warming on Natural and Human Systems. in *Global Warming of 1.5°C* 175–312 (Cambridge University Press, 2018). doi:10.1017/9781009157940.005.

50. Armstrong McKay, D. I. *et al.* Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science (80-.).* **377**, (2022).

51. Lenton, T. M. *et al.* Climate tipping points — too risky to bet against. *Nature* **575**, 592–595 (2019).

52. Hoesly, R. M. *et al.* Historical (1750--2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS). *Geosci. Model Dev.* **11**, 369–408 (2018).

53. Byers, E. *et al.* AR6 Scenarios Database. (2022) doi:10.5281/ZENODO.5886912.

Methods

Models included

Four global integrated assessment models are included in this research: GCAM-PR (also referred to as GCAM), GEMINI-E3 (also referred to as GEMINI), MUSE, and TIAM-Grantham (also referred to as TIAM). These are selected to reflect the broad diversity of modelling theories, spanning a range from least-cost energy system optimisation to partial and general equilibrium and to agent-based modelling. Diversity of modelling structure, theory, and solution is typically sought in multi-model studies, aiming to reach robust estimates by reflecting structural uncertainty—rather than parametric uncertainty, which has been minimised to reduce unwanted response heterogeneity[40].

GCAM[54] (Global Change Analysis Model) is a partial equilibrium IAM, achieving equilibrium between energy supply and demand in each represented sector, accounting for the changes in energy prices resulting from changes in fuels and technologies used to satisfy energy-service demands in these sectors. The model operates on a 'recursive dynamic' cost-optimisation basis and solves for the least-cost energy system (constrained by observed technological preferences) in a given period before moving onto the next period and performing the same process.

TIAM[55] (Times Integrated Assessment Model) is also a partial equilibrium IAM and achieves similar equilibrium between energy supply and demand in each sector. However, TIAM operates on a 'perfect foresight' welfare cost-optimisation basis, whereby all consequences of technology deployments, fuel extraction, and energy price changes over the entire time horizon are considered when minimising the cost of the energy system to provide energy-service demands within specified emissions constraints.

GEMINI-E3[56] (General Equilibrium Model of International–National Interactions between Economy, Energy and the Environment) differs in model solution in that it is a general equilibrium IAM, featuring a more detailed, multiple-sector representation of the economy that considers how the impacts of specific policies spread across economic sectors and regions affect environmental parameters. This means that, despite also being driven by market equilibrium, this equilibrium is assumed to take place simultaneously in each market/region. Its richer representation of the economy requires calibration to data on national and international socio-accounting information and a vector of various elasticities of substitution, but it allows endogenous calculation of market prices of inputs and outputs.

Finally, MUSE[57] (ModUlar energy systems Simulation Environment) is an agent-based, energy system model that provides a detailed account of the energy sector to calculate least-cost GHG emissions reduction pathways—or the costs of alternative climate policies. It is bottom-up, in that assumes short-term microeconomic equilibrium on the energy system by iterating market clearance across all sector modules and interchanging price and quantity of each energy commodity in each region, but it is also agent-based, in that it tries to determine a mitigation pathway by providing an as-realistic-as-possible description of the investment and operational decision making in each geographical region within a sector.

All four models differ in the way technologies are chosen across sectors: GCAM employs a logit technology choice mechanism, which causes gradually decreasing returns as a technology is further diffused; TIAM uses a winner-takes-all optimisation mechanism, implying that the cheapest technology can dominate all new deployment; GEMINI uses a nested constant elasticity of substitution function; while MUSE follows an agent-based approach, where agent decision goals and strategies determine technology choices in each time step. Detailed model documentation for all four models is available online at https://www.i2am-paris.eu/detailed_model_doc.

Scenario protocol

Starting this modelling exercise, harmonised socio- and techno-economic input assumptions were applied by all models, reflecting the latest available information and avoid "noise" in the model outcomes related to unaligned assumptions[40]. For GDP projections, the IMF WEO of April 2022[58] for GDP growth until 2027 the OECD EO-109 (2021)[59] for post-2027 growth projections, reflecting the impacts of the COVID-19 pandemic as well as initial estimated impacts related to the Ukraine conflict. On techno-economic assumptions, power generation technology costs were updated to observed 2020 values (IRENA) while maintaining the future evolution of costs as reflected in Giarola et al (2021)[40]. For hydrogen, projections of different production technologies were updated according to IEA estimates (2017)[60]. It should be noted that, despite considerable efforts to harmonise model inputs, the four IAMs do not all represent the same portfolio of technologies; this hampers the efforts of reducing unwanted heterogeneity of responses and of attributing the resulting model spread only to structural uncertainty. However, our multi-model assessment remains useful in that it provides an implicit assessment of the variety of pathways that could result not just from structural differences, but also from different assumptions around the availability of key technologies (e.g., direct air capture[61,62]).

The first scenario (Current Policy extrapolated with Emission Intensity, CP_EI) is based on the current portfolio of actual emission reduction policies as well as credible policy targets until 2030 in G20 countries including the entire European Union (EU) (see Supplementary Data 1). Post-2030 action is then modelled by measuring the average rate of change in emissions intensity of GDP from 2020 to 2030 in each region and assuming emissions intensity reduction rates will remain the same after 2030. This method is also used by Ou et al (2021)[22], Sognnaes et al (2021)[18] and VanDyck et al (2016)[15] to assess the long-term implications of NDCs. The applied policy targets until 2030 (e.g., renewable energy mx targets, vehicle fuel standards) are maintained as minimum levels beyond 2030 to avoid backtracking of achieved policies.

The second scenario (NDCs extrapolated with Emission Intensity, NDC_EI) is based on stated 2030 emission targets captured in NDCs submitted or announced by June 2022, capturing all mitigation ambition updates related to the COP26 in Glasgow (see Supplementary Table 1). These NDC targets are applied on top of current policies (CP) modelled in the previous scenario; in model regions where current policies overachieve on the mitigation targets in NDCs, no additional emission constraints are applied, following Sognnaes et al (2021)[18]. Emissions reductions in NDC scenarios are therefore never less ambitious than what CP implies. The same emission intensity method is applied for post-2030 action as in CP_EI.

The third and most ambitious scenario (NDCs with Long-Term Targets, NDC_LTT) is built on the NDC_EI until 2030 but, for regions that expressed an LTT, such as net-zero commitments or other targets for 2050 or later (either in law, policy documents, or only announced) (see Supplementary Table 2), emission constraints are applied that linearly decline from 2030 emissions as in the NDC_EI scenario towards said long-term target. For regions without LTTs, post-2030 emissions follow an identical path as in the NDC_EI scenario.

Since nearly all countries have submitted at least some NDC target, defining NDC targets for aggregated model regions is relatively straightforward. However, far but all countries have submitted LTTs, hence some assumptions are required if one or more countries in an aggregated model region have LTTs. In such cases, the emissions level (E) should be calculated by applying the LTT to the estimated emissions share of that specific country (i) in the entire model region (j) according to either the 2019 emissions levels[52], or, if available, the country´s emissions share in the aggregated NDC target for 2030, and applying the EI method for the rest of the region:

$$E_{j,2050} = E(LTT)_{i,2050} \times \left(\frac{E_{i,2019\,/\,2030}}{E_{j,2019\,/\,2030}}\right) + E(EI)_{j-i,2050} * \left(\frac{\left(E_{j,2019\,/\,2030} - E_{i,2019\,/\,2030}\right)}{E_{j,2019\,/\,2030}}\right)$$

Temperature assessment

To assess the implications of the modelled scenarios for global mean temperature increase, emission outcomes from the models are harmonised with historical tendencies, infilled to include the full set of greenhouse gas emissions, and fed into a climate model for probabilistic temperature simulations.

In most instances, the first stage of the temperature assessment is to harmonise the global emissions trajectories to known values in 2015 (interpolated if not already present) using ratio-based harmonization approach[63]. Since not all models report the entire set of GHGs and other pollutants required for a complete temperature assessment, unreported emissions from each model participating in this intermodal comparison exercise are infilled using Silicone v1.3.0[64], using a quantile rolling window with CO_2 emissions from energy and industrial processes as the lead emissions, and based on an infilling database comprised of the harmonised AR6 database[53] filtered to match the model philosophy. The models that are included in the AR6 database are categorized based on their model type (for example general equilibrium/ partial equilibrium) and solution type (recursive dynamics/ inter temporal). The exception to this is the F-gases (SF6, HFCs and PFCs), which are not reported by enough models in each category. For these cases (where not reported otherwise), we use the F-gas total infilled as above, then break it down into its component SF6, HFC total and PFC total using the whole harmonised AR6 database and the Silicone technique DecomposeCollectionTimeDepRatio. For the GEMINI-E3 model simulating global economy dynamics over the time horizon 2015 to 2050, we extend each of the emissions till 2100 for each scenario using the Silicone tool ExtendLatestTimeQuantile, using the whole AR6 database. Plotting the infilled trajectories of Kyoto gases instead of fossil CO_2 produces very similar results, as fossil CO_2 correlates well with the Kyoto gas total in the AR6 database (see Supplementary Figure 3), and our infilling technique preserves the correlation between the modelled gas and all the constituents.

When we have a complete set of required emissions, they are run through the simple climate model FaIR version 1.6.2, calibrated to match the AR6 Working Group 1 climate assessment[65,66]. This four-box model of the world replicates the impact of emissions on atmospheric concentrations, climate forcings and temperatures, constrained both against observations and the probability distributions of fundamental climate characteristics like TCR assessed by the IPCC.

Supplementary Figure 4 shows the median temperature assessments until 2100 from FaIR, while also showing the uncertainty in this temperature assessment related to infilling the emission trajectories using Silicone.

Climate action gap definition

Comparing scenario outcomes allows us to subdivide the climate action gap—i.e., the difference between the emission reductions and related temperature outcomes that can be expected with the current set of policies in all countries, with the goal of keeping global temperature increase below 1.5°C. It is with these two trajectories (current policies as in "where we stand" and 1.5°C as in "where we want to go") and the two intermediate trajectories (NDCs as in "ambition reflected in near-term targets" and LTTs as in "ambition reflected in long-term targets") that we define the different gaps in this study. The first gap, hereby termed 'implementation gap', refers to the difference in 2100 or peak temperature (depending on whether a peak is reached in the 21st century) of current policies and that of 2030 NDCs, both extended by EI trends. The second gap, hereby termed 'long-term ratchet gap', refers to the temperature difference between the 2030 NDCs extended by EI trends, on the one hand, and the 2030 NDCs followed by LTTs (where stated), on the other—in other words, it refers to the pace, in which post-2030 action must be accelerated relative to pre-2030 action to deliver on long-term targets. The final gap, hereby termed 'ambition gap', refers to the difference between the peak temperature of 2030 NDCs followed by available LTTs and the 1.5°C target. These three gaps, altogether making up the climate action gap, are illustrated in detail in Figure 1 and are not to be confused with the UNEP definition of 'emissions gap'[19]; the latter refers to the emissions difference between the promised reductions (as in NDCs and/or LTTs) and the needed reductions (as in least-cost pathways delivering 1.5°C), which we do not calculate.

Feasibility assessment

This study looks into the feasibility of pathways based on country-specific policies and announced targets, with the objective to identify "where" (which country and sector) and "when" (which decade between 2020 and 2050) we find the largest bottlenecks to achieving them. This feasibility analysis builds largely on the Brutschin et al (2021)[37] framework, measuring feasibility concerns by comparing specific model outcomes with threshold values found in the literature. It also defines feasibility as in that framework, i.e., as the degree to which a scenario lies within the boundaries of diverse societal capacities for change in a given period. However, the reflected dimensions are largely constrained by the capacity to quantify with all models used in this study, while overlapping dimensions are avoided to allow a fair comparison of feasibility concerns between models.

The feasibility analysis looks at specific variables in model outcomes and compares these with several thresholds found in literature. A total of 10 different feasibility indicators are measured, which can be divided into 3 categories: (a) socioeconomic feasibility concerns related with the cost burden of mitigation policies, (b) technology scale-up feasibility concerns related with the velocity at which clean technologies replace existing technologies in place, and (c) physical feasibility constraints related with the physical potentials for bioenergy production and carbon storage. Therefore, our analysis does not include bottom-up socio-political dimensions that cannot be quantified in (all) our models, and our definition of feasibility should not be interpreted as broadly as defined in literature[67,68] but defined by the modelled dimensions considered—hence, we discuss 'feasibility concerns' rather than feasibility.

Feasibility concerns are measured by model region and 10-year period (2020-2030, 2030-2040 and 2040-2050) to illustrate "where" and "when" we find the largest bottlenecks to climate change mitigation. Identically for all indicators, a value of the size of 1 represents that the specific threshold for that indicator is surpassed by 100% in that specific model region and period. Similarly, scores of 0.5 and 1.5 mean surpassing the thresholds by respectively 50% and 150%. That also means that, as long as the threshold is not passed, even if it comes close, the feasibility concern is measured as zero. Similarly for all indicators, the global value is built up as a weighted average of the independent values in all model regions. The weighting variable, however, varies between the different indicators (see Table 2). For more details on how the different feasibility indicators are approached, on the precise threshold levels as well as the sources these levels are taken from, see Supplementary Section 2. For the precise feasibility concern levels under centrally assumed threshold as well as under threshold uncertainty (Figure 3b), see source data for figures 3 and 4.

Data availability

The datasets generated during, and analysed in, the current study are available from a public repository (https://doi.org/10.5281/zenodo.7767193).

Code availability

The code availability for the individual models used in this paper varies and contact should be made to individual modelling groups. The GCAM model is available for download from https://github.com/JGCRI/gcam-core. The code for the temperature analysis (FaIR + Silicone) is available from a public repository (https://github.com/Rlamboll/post-Glasgow_climate_targets).

Methods-only references

54. Calvin, K. *et al.* GCAM v5.1: representing the linkages between energy, water, land, climate, and economic systems. *Geosci. Model Dev.* **12**, (2019).

55. Loulou, R. & Labriet, M. ETSAP-TIAM: the TIMES integrated assessment model Part I: Model structure. *Comput. Manag. Sci.* **5**, 7–40 (2008).

56. Bernard, A. & Vielle, M. GEMINI-E3, a general equilibrium model of international–national interactions between economy, energy and the environment. *Comput. Manag. Sci.* **5**, 173–206 (2008).

57. Giarola, S., Sachs, J., D'Avezac, M., Kell, A. & Hawkes, A. MUSE: An open-source agent-based integrated assessment modelling framework. *Energy Strateg. Rev.* **44**, 100964 (2022).

58. IMF. World Economic Outlook Database April 2022. (2022).

59. OECD. Economic Outlook No 109 - October 2021. (2021).

60. Collodi, G. *et al. Techno-economic evaluation of SMR based standalone (merchant) hydrogen plant with CCS*. (2017).

61. Grant, N., Hawkes, A., Mittal, S. & Gambhir, A. The policy implications of an uncertain carbon dioxide removal potential. *Joule* **5**, 2593–2605 (2021).

62. Fuss, S. *et al.* Negative emissions—Part 2: Costs, potentials and side effects. *Environ. Res. Lett.* **13**, 063002 (2018).

63. Gidden, M. J. *et al.* A methodology and implementation of automated emissions harmonization for use in Integrated Assessment Models. *Environ. Model. Softw.* **105**, 187–200 (2018).

64. Lamboll, R. D., Nicholls, Z. R. J., Kikstra, J. S., Meinshausen, M. & Rogelj, J. Silicone v1.0.0: an open-source Python package for inferring missing emissions data for climate change research. *Geosci. Model Dev.* **13**, 5259–5275 (2020).

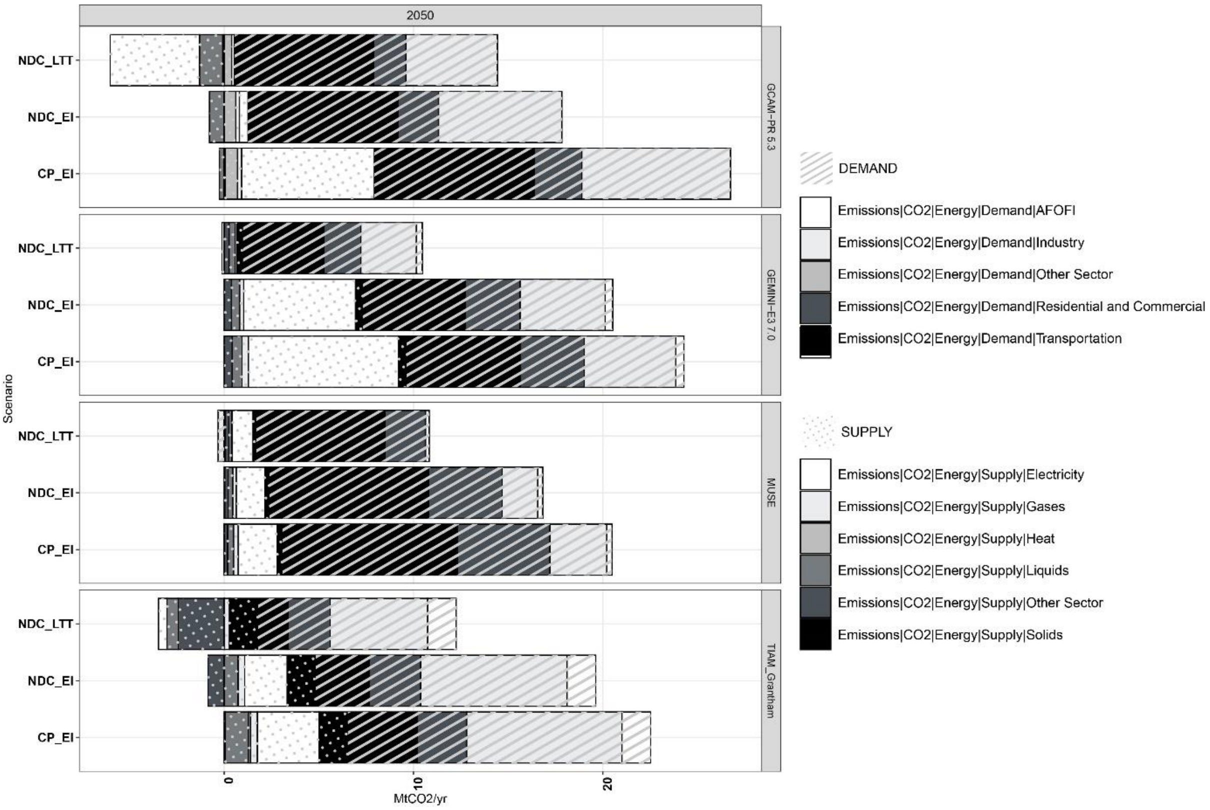
65. Nicholls, Z. *et al.* Cross-Chapter Box 7.1: Physical emulation of Earth System Models for

scenario classification and knowledge integration in AR6. in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, 2021).

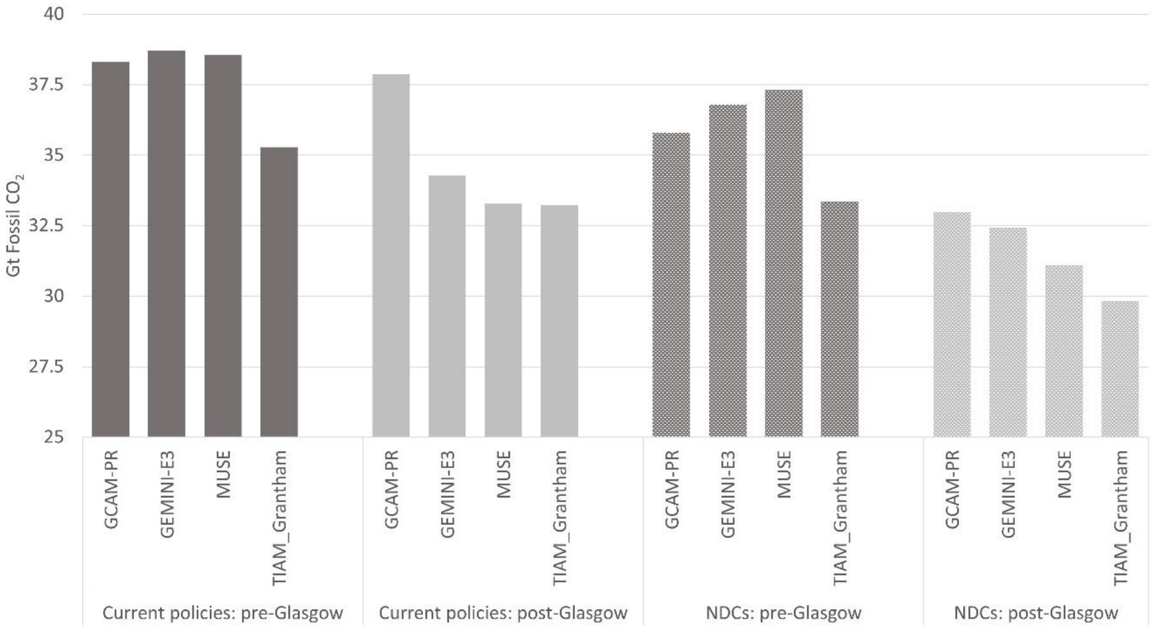
66. Smith, C. J. *et al.* FAIR v1.3: a simple emissions-based impulse response and carbon cycle model. *Geosci. Model Dev.* **11**, 2273–2297 (2018).

67. Stern, P. C., Dietz, T. & Vandenbergh, M. P. The science of mitigation: Closing the gap between potential and actual reduction of environmental threats. *Energy Res. Soc. Sci.* **91**, 102735 (2022).

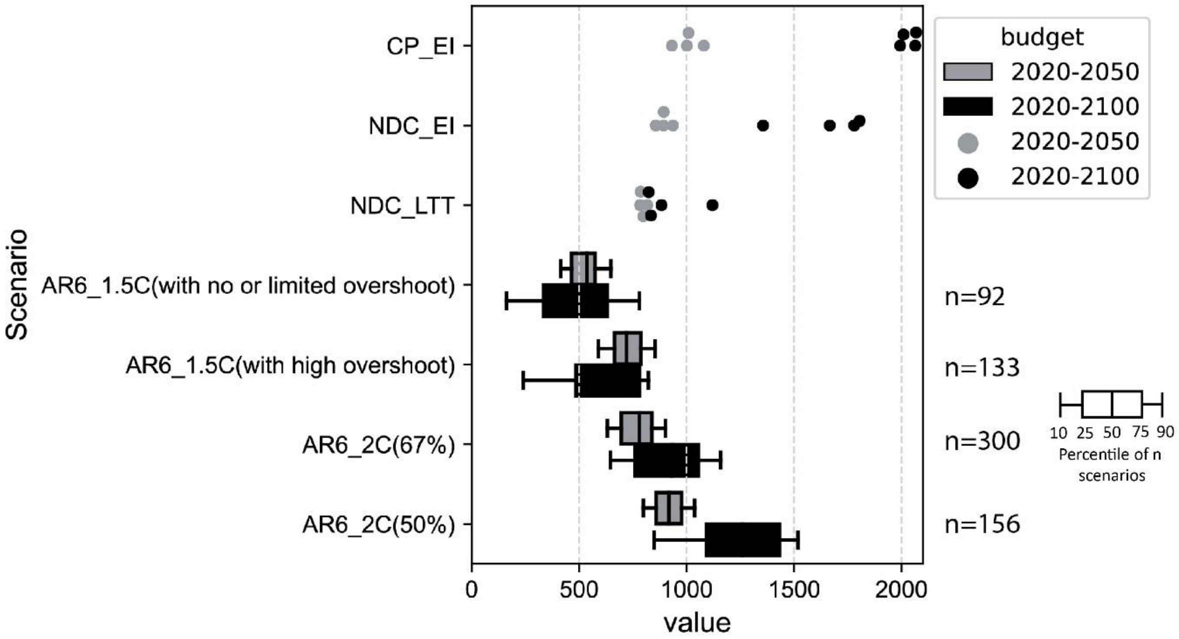
68. Stern, P. C., Dietz, T., Nielsen, K. S., Peng, W. & Vandenbergh, M. P. Feasible climate mitigation. *Nat. Clim. Chang.* **13**, 6–8 (2023).



Extended Data Fig. 1 | 2050 CO2 by sector. Remaining global CO2 emissions from different sectors for each model, in 2050.



Extended Data Fig. 2 | Comparison of pre- and post-Glasgow emissions. Comparison of pre- and post-Glasgow current policy and NDC 2030 global emissions.
Pre-Glasgow emissions are taken from Sognnaes et al (2021) referring to CP_Intensity and NDC_Intensity scenarios.



Extended Data Fig. 3 | Comparison with AR6 scenarios emission ranges. Boxplots of cumulative emission ranges (from 2020 (included) to 2050 and 2100) for all three scenarios in this study, compared with cumulative emissions in c1, c2, c3 and c4 mitigation scenarios from IPCC AR6 database.