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Feasibility of peak temperature targets in light of institutional constraints

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Despite faster-than-expected progress in clean energy technology deployment, global annual CO_2 emissions have increased from 2020 to 2023. The feasibility of limiting warming to 1.5 °C is therefore questioned. Here we present a model intercomparison study that accounts for emissions trends until 2023 and compares cost-effective scenarios to alternative scenarios with institutional, geophysical and technological feasibility constraints and enablers informed by previous literature. Our results show that the most ambitious mitigation trajectories with updated climate information still manage to limit peak warming to below 1.6 °C ('low overshoot') with around 50% likelihood. However, feasibility constraints, especially in the institutional dimension, decrease this maximum likelihood considerably to 5–45%. Accelerated energy demand transformation can reduce costs for staying below 2 °C but have only a limited impact on further increasing the likelihood of limiting warming to 1.6 °C. Our study helps to establish a new benchmark of mitigation scenarios that goes beyond the dominant cost-effective scenario design.

Global temperature rise is expected to peak around the time when global CO_2 emissions reach net-zero levels[1,2]. Reaching global net-zero CO_2 emissions quickly while limiting cumulative emissions therefore lies at the core of achieving the long-term goal of the Paris Agreement[3,4]. The level of peak temperature and the speed at which it is reached determines the adaptation needs for infrastructure and natural systems[5]. The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6)[6] assessed a large number of scenarios and categorized them based on various metrics, including their projected peak temperature, and found a relatively large number (97) of scenarios still limiting warming to 1.5 °C with no or limited overshoot, defined as peak temperature below 1.6 °C with >50% likelihood. However, the feasibility of these have been questioned[7,8], and recent emissions increases from 2020 to 2023[9] have underscored those doubts.

In addition, since AR6, continued measurements and advances in climate science have led to a downward correction of remaining carbon budgets for a given peak temperature target[10]. Furthermore, the understanding of the feasibility of near-term deployment of different mitigation options has improved with continued deployment (or lack thereof). Studies looking into feasibility aspects[8,11–13] have also highlighted the difficulty of fast emissions reductions as part of dedicated climate policies, especially in countries that lack the governance and institutional capabilities to enforce regulation in other policy domains (such as taxation or environmental regulation).

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Table 1 | Treatment of five feasibility dimensions taken from IPCC AR6 in this study

Feasibility dimension	Geophysical	Technological	Institutional	Socio-cultural	Economic
Scenario name components	'Tech'		'Institutional'	'Enablers'	
Use in study	Combined constraint		Policy design constraints with three subcases (optimistic, default and pessimistic) (Fig. 1)	Enabling factor via reduced constraint	Result metric
Variables	Limit on yearly bioenergy potential, cumulative geological storage of carbon	Growth of carbon capture and storage (CCS), nuclear, solar, wind and gas electricity+ generation (maximum deployment levels at different time horizons or annual rate of change of market shares)	Regional carbon price differentiation and capping of carbon prices (and capping of emissions reduction in default and pessimistic case)	Behavioural changes reducing energy demand, especially for high-income activities and countries; reduced constraint on electrification	Carbon prices

Details and motivation Methods and Supplementary Information sections 2–4.

Our study thus explores the feasibility of ambitious peak temperature targets in the Paris Agreement target range, in light of the current state of knowledge, taking into account the observed emissions rebound after the COVID-19 pandemic[14] and the improved understanding of feasibility[8,11–13] along five relevant dimensions (Table 1): geophysical, technological, institutional, socio-cultural and economic. Using eight state-of-the-art global multi-regional process-based integrated assessment models (IAMs), we explore a set of 20 scenarios (Methods and Supplementary Table 1), including both the cost-effective settings that dominate the IPCC scenario assessments and scenarios with harmonized variation of explicit feasibility considerations (Table 1). The choice for this treatment is informed by previous studies and the participating models' capabilities and is not fully comprehensive in the sense that additional variables and aspects[15] could also be assessed. However, we use a more systematic approach than previous studies'[16,17] scenarios and also assess the impact with and without regional differentiation, both of which have been identified as crucial missing pieces in previous studies[18–21].

We explore the impact of explicit consideration of feasibility constraints on six scenarios that limit peak warming to less than 2 °C with more than 66% likelihood (defined as a 1,000 Gt CO_2 carbon budget from 2018) and additionally explore the lowest end of achievable peak temperature under variation of feasibility assumptions in 14 additional scenarios. Complementary to other studies looking at the role of short-lived climate forcers[22] or individual energy sectors or technologies[23–26], we focus here on total CO_2 emissions and especially on the energy sector (details of the modelling in Methods and Supplementary Information sections 2–4). Thus, we only evaluate the warming implication via the link with cumulative CO_2 emissions. The models used in this analysis do include other greenhouse gases—including methane (CH_4), which is very important for understanding the trajectory of peak temperatures[27]. However, due to the lack of available evidence regarding the levels of CH_4 emissions reductions that are considered feasible and the large differences of representation across models, we limited this analysis to CO_2. The key innovation beyond existing literature lies in the consideration of the institutional dimension with which we strive to proxy the capacity to effectively implement climate mitigation policies. We justify this key assumption based on past literature that has identified the quality of institutions as an important driver of many climate mitigation policies[28–31] and the credibility of their implementation[32]. We then operationalized institutional constraints via region-specific limits on both carbon prices and emissions-reduction rates, which are derived as a stylized function of the dynamically projected government effectiveness indicator[33] and historically observed reductions of sulfur dioxide emissions (Supplementary Information section 4A). This constraint is thus region specific and changes over time as the government effectiveness improves (Fig. 1a). Within this institutional dimension, we also analyse a more pessimistic alternative setting of 'frozen' governance indicators and a more optimistic setting in which only carbon prices and their spread are limited. Additional details provided in Fig. 1, Methods and Supplementary Information section 4A.

The logic behind this approach is to explicitly incorporate the most relevant feasibility considerations identified in previous studies[6,11], making the scenarios more applicable for real-world interpretation and implementation. In other words, the inclusion of technological and institutional constraints helps scenarios to be closer to the fuzzy feasibility space, allowing them to also have a higher implicit likelihood of being realized (at least based on the assessment of aspects covered). Following recent critiques of the often narrow focus on mitigation costs in IAM studies[34], we thus explicitly look at scenarios with higher narrowly defined mitigation costs but lower risk of failure[35]. The additional enablers of reduced demand[36,37] in high-income countries and increased electrification[38] in the combined 'Tech and Enablers and Institutional' scenarios create more flexibility on the supply side and thus further improve the feasibility of implementation. This approach is illustrated in Fig. 2 that situates our scenarios in the feasibility framework by Jewell and Cherp[39], adapted to climate scenarios instead of single mitigation options.

Interaction of different feasibility dimensions

To explore implications of feasibility constraints on the cost and achievability of climate targets, we first explore carbon prices to limit cumulative CO_2 emissions from all sectors from 2018 until the time of net-zero to 1,000 Gt CO_2 (this section) and then explore minimum achievable cumulative CO_2 emissions across different feasibility-scenario variants (following section).

The technological constraints do not have a substantial impact in terms of overall difficulty and the relative effort required for reaching an ambitious decarbonization trajectory, which we estimate via the shadow price of carbon (Fig. 3). The relative change of the uniform carbon prices is for most models smaller than a factor of two and is also smaller than the difference across models for the same assumptions (Extended Data Fig. 1). The imposition of the institutional feasibility is assessed first in its default specification of both constrained prices and quantities. This leads to the differentiation of relative effort across regions (Fig. 3 shows the highest and lowest regional values). Countries with very low governance scores exhibit carbon prices below the

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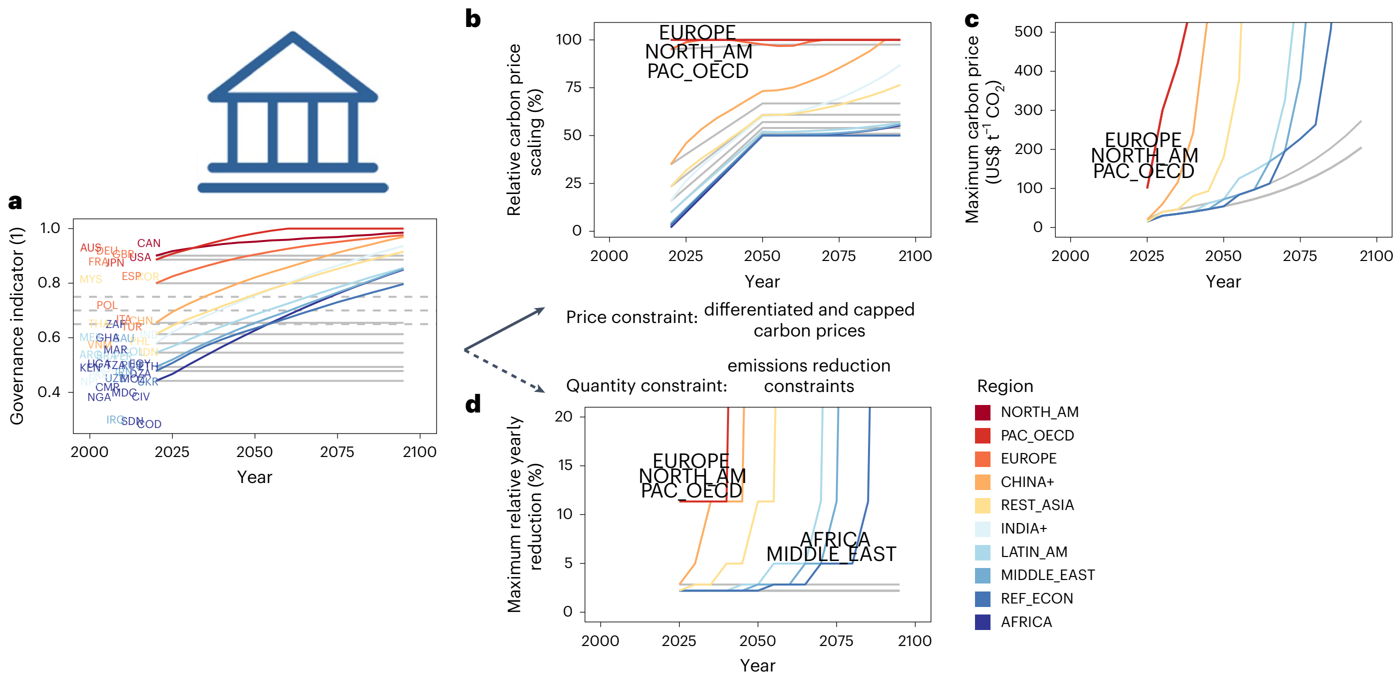

Fig. 1 | Implementation of institutional constraint. a, Governance indicator data (based on Andrijevic et al.[33]) for countries with a population of more than 25 million in 2020 (identified by ISO-3 country codes) and evolution for ten harmonized IPCC regions and the threshold values used for the binning of maximum carbon prices and reductions in dashed grey horizontal lines. The relationship between 2020 governance indicators and per capita gross domestic product (GDP) is shown in Extended Data Fig. 2. **b**, Scaling of carbon prices relative to the maximum. **c**, Maximum carbon prices. **d**, Maximum relative yearly reduction of fossil fuel and industry CO_2 emissions. Regions with identical values are highlighted by additional region labels. The thin grey lines in each panel indicate the settings under the assumptions of frozen governance, so without improvement of the governance indicators across regions.

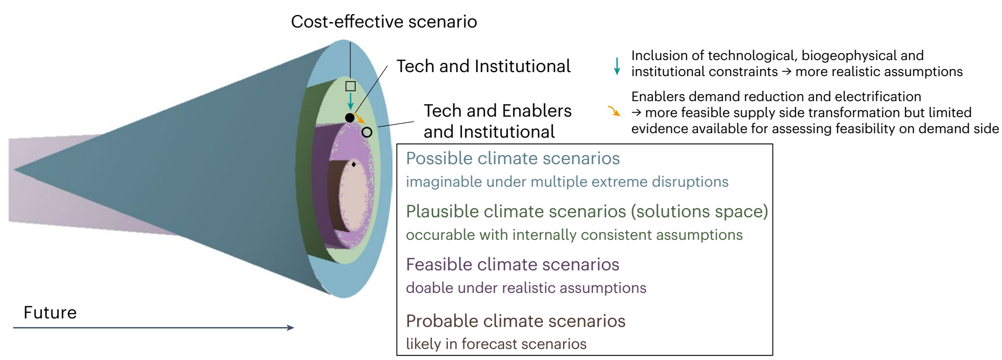

Fig. 2 | Futures cone adapted to climate scenarios. The new scenarios in this study are closer to the (fuzzy) feasibility space than existing reference mitigation scenarios that target cost effectiveness, not feasibility. Scenarios that assume the socio-cultural enablers cannot unambiguously be assigned higher or lower feasibility as they are more doable in terms of their supply-side transformation but might be less doable regarding the assumed demand transformation. Figure adapted with permission from ref. 39 under a Creative Commons license CC BY 4.0.

Cost-effective-scenario level; for the highest-capacity countries, carbon prices increase between a factor 2 and 3 for most models compared with the Cost-effective scenario, leading to a shift of regional emissions. However, combining both the technological and institutional constraints leads to strong increases of carbon prices in high-capacity countries by a factor of 3–4 for most models. This strong nonlinear effect of adding both the technological and institutional constraint can be explained by the increased importance of fast upscaling of all mitigation technologies for the high government effectiveness regions that need to reach net-zero CO_2 earlier in scenarios with institutional constraint. Therefore, the regionalized constraint on solar and wind upscaling is more constraining for faster decarbonizing regions. And even the globally implemented constraints on the crucial technologies carbon capture and storage (CCS) and bioenergy for reaching net zero become more constraining compared with the scenario without institutional constraint, as overall reliance on carbon dioxide removal increases in such scenarios of differentiated speeds[17].

Dedicated interventions on socio-cultural enablers (for example, the reduction of energy demand for high-income regions and more optimistic assumptions on electrification) substantially reduce CO_2 prices so that in some models even the highest-income regions have lower carbon prices compared with the Cost-effective case. Even with the additional technological constraints on the supply side, the combined scenario (Tech and Enablers and Institutional) achieves the target with only a doubling of carbon prices in high-institutional-capacity countries and reduced carbon prices in countries with the lowest governance scores (which closely coincides with lowest income; Extended Data Fig. 2). Absolute carbon prices in this scenario for regions with highest government effectiveness are still at a challenging and high level, but for four out of seven models below US$100 t^{-1} CO_2 in 2030

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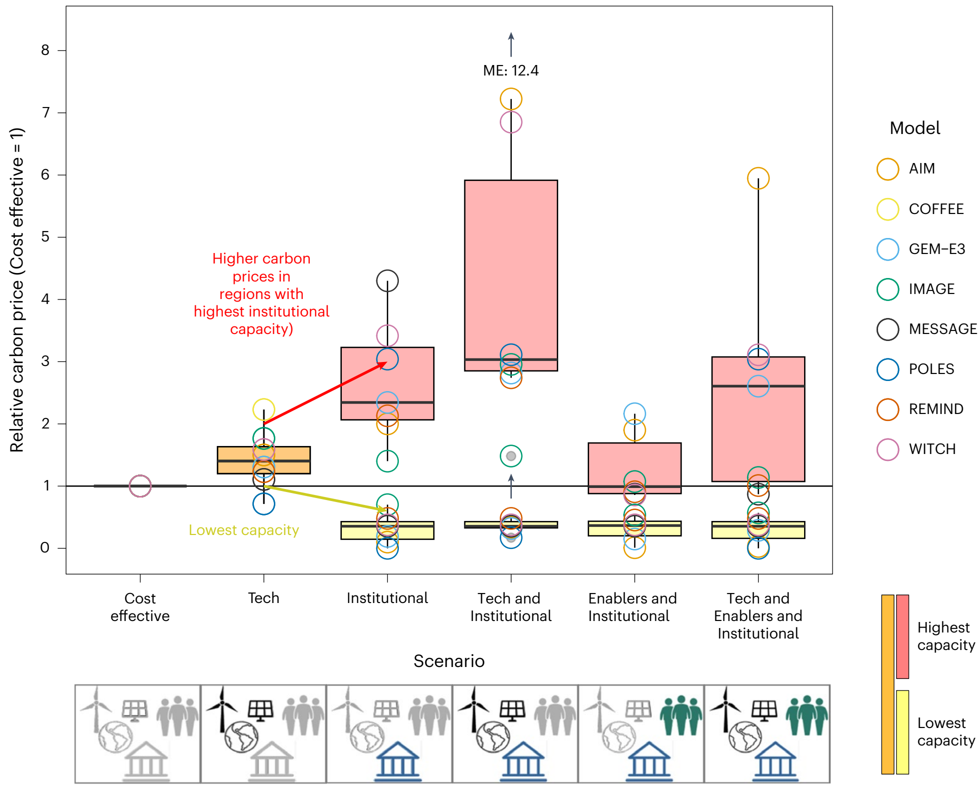

Fig. 3 | Relative carbon prices in 2050 as a function of feasibility setting. Relative carbon prices compared with Cost-effective set-up for the regions with lowest and highest institutional capacities in different scenarios with a 1,000 Gt CO_2 budget from 2018 until the year of net-zero CO_2 (corresponding to a higher than 66% likelihood of limiting warming to below 2 °C). Carbon prices are harmonized across regions in the first two scenario variants (and shown in orange) and differentiated for the other four. For clarity, only the highest and lowest carbon prices for each model are shown (in red and yellow, respectively), with relative prices of the remaining regions being situated in between. The box plot shows the median (centre line), interquartile range (box) and full range (whiskers) across the models shown, with outliers further noted by a grey dot and arrow. Note that the outlier from the MESSAGE model is outside the plot range ('ME'). The institutional dimension is using the default specification of dynamic governance scores and combined price and quantity constraints (Fig. 1).

(Extended Data Fig. 1). Despite the lack of comprehensive global mitigation action and increasing global emissions in the past 15 years, the faster-than-expected technological progress has kept ambitious mitigation feasible at manageable efforts. This is in contrast to prominent earlier work that had not anticipated such fast progress and concluded that immediate fully harmonized participation from 2010 is required to stay below 2 °C (ref. 40). A comparison of the shadow carbon prices we find here (which measures the marginal cost of abating a ton of CO_2) with the social cost of carbon (which measures the monetized value of avoided damages of such abatement) should not be misinterpreted as a full cost–benefit analysis. Nevertheless, it is worth noting that recent literature has put the median social cost of carbon at values between US$150 and US$200 per ton of CO_2 in 2020, with substantially higher means[41–43], higher than the 2030 carbon prices in regions with high government effectiveness, and much higher than those with low government effectiveness (Extended Data Fig. 1). The fact that the Tech and Enablers and Institutional scenario explicitly considers feasibility constraints implies that such a scenario represents a more plausible pathway towards climate-target achievement than the Cost-effective setting that so far has dominated most scenario analyses. The implications on regional emissions trajectories, including regional reductions until 2040 and net-zero dates, and technology choice of this difference are explored in detail in a parallel publication currently in preparation (E. B. et al., manuscript in preparation).

Lower bound of peak temperatures

If we assume that governance scores remain frozen at their 2020 levels, the ability to rapidly constrain emissions in most regions is sharply curtailed. In such a situation, and combined with technological constraints and the more pessimistic demand-side assumptions, more than 1,000 Gt CO_2 would still be emitted before net zero can be reached. With these pessimistic assumptions on feasibility constraints (not included in the previous section and Fig. 3), the maximum allowable policy ambition achieves peak temperature of 2 °C only with around 30–50% likelihood (left-hand side of Fig. 4a and comparison with Fig. 4b with identical *y* axis).

Keeping the pessimistic frozen institutional constraints but relaxing the technological constraint or assuming faster demand-side transformation helps to lower achievable peak budgets and temperatures, with the models diverging on which effect is larger. The models do agree, however, that the combined relaxation of the technological and socio-economic dimension allows for peak budgets between 750 and 900 Gt CO_2, corresponding to 40–55% likelihood of staying below 1.8 °C (Fig. 4a,b).

Under the default specification of dynamically improving governance scores for the institutional constraint, results are more diverse across models, with MESSAGE, POLES and WITCH at the more pessimistic high end of the carbon budget and temperature range, and GEM-E3, IMAGE and REMIND at the lower end. With the most pessimistic assumptions on technological and socio-cultural constraints (Tech and Institutional), they cluster around 900–1,000 and 550–700 Gt CO_2, respectively, which corresponds to either around 40% probability of staying below 1.8 °C or around 75%, respectively. With the more optimistic assumptions on technological and/or socio-cultural constraints, the range of likelihood to stay below 1.8 °C reaches 50–90%, which corresponds to a 15–50% likelihood of staying below 1.6 °C.

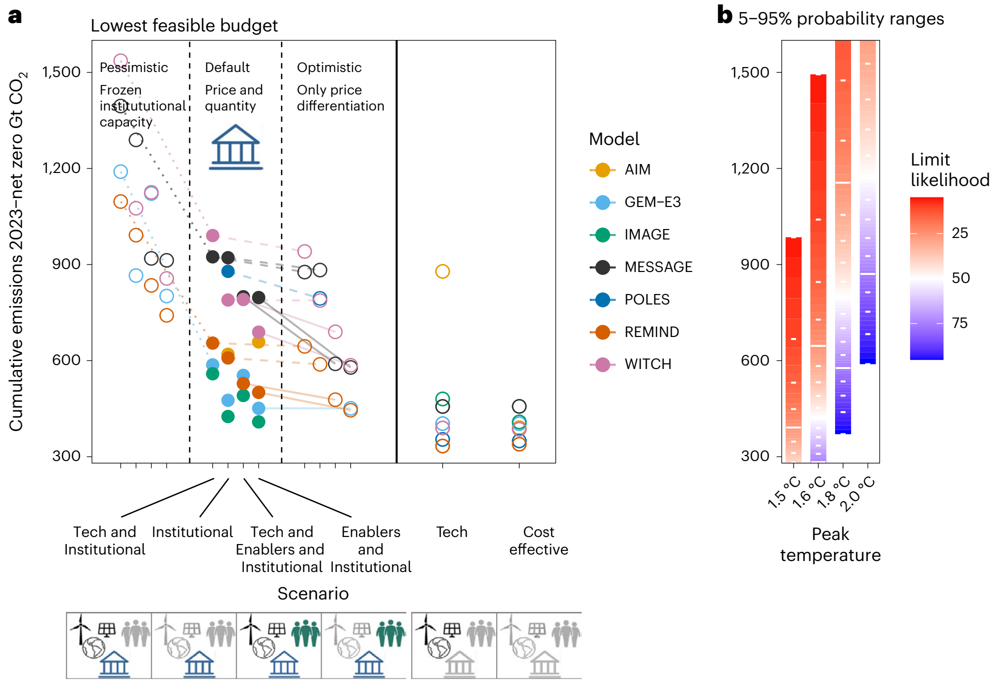

Fig. 4 | Minimum achievable carbon budget and peak temperature likelihood. a,**b**, Minimum achievable carbon budget from 2023 until net-zero CO_2 across 14 different feasibility variants (**a**) and corresponding likelihood of staying below 1.5 °C, 1.6 °C, 1.8 °C and 2.0 °C at peak according to Table 7 in Forster et al.[10] (**b**). Likelihoods all assume the median of non-CO_2 contribution towards peak warming. In **a**, full symbols in the middle show the default assumption of combined differentiation of carbon prices and emissions-reduction quantities, whereas the four options on the left with open points show the results assuming no improvement of institutional capacity over time. The open points on the right side show the more optimistic assumption of only differentiated carbon prices but without the explicit emissions-reduction constraints.

Put differently, with these settings, some but not all models still reach the C1 class of scenarios from IPCC AR6 (defined as having >50% likelihood of a peak below 1.6 °C).

Even a more optimistic implementation of the institutional constraint, which differentiates carbon prices but does not explicitly constrain emissions reductions, leads to similar results. Not all models have run these scenario variants, but the comparison of scenarios from the same models (indicated by the connecting lines in Fig. 4) shows that the effect is slightly larger for scenarios with enablers (solid lines) than for scenarios without (dashed lines). Therefore, all models running scenarios with enablers and this more optimistic institutional constraint achieve scenarios in the C1 class.

For scenarios without any form of institutional constraint, nearly all models achieve C1 compatible scenarios, both with and without additional technological constraints. The exception is the AIM model in which, due to very strong growth of assumed electricity demand to 2030 (+1,900 TWh yr^{-1} from 2022 to 2030, compared with an average of +600 TWh yr^{-1} from 2010 to 2022; Extended Data Fig. 3), renewables scale up is not fast enough to allow for the necessary pace of fossil phase out in the electricity sector[44]. Therefore, in scenarios without Tech constraints, this model projects what are probably unrealistically high rates of growth of fossil CCS to 2030 based on the recent track record of those technologies. AIM thus projects a very slow phase out of unabated fossil fuels in electricity generation in the Tech scenario, causing most of the more than 300 Gt CO_2 higher emissions in the Tech scenario compared with the Cost-effective scenario.

Discussion

Our results show that the most ambitious scenarios accounting for the institutional feasibility concern only allow for a likelihood of 5–45% of staying below 1.6 °C at peak warming, with considerable differences across models and assumptions around the institutional constraints. The world needs to be prepared for the possibility of an overshoot of the 1.5 °C limit by at least one and probably multiple tenths of a degree even under the highest possible ambition. Without much increased near-term climate policy ambition everywhere, and especially without dedicated efforts to improve institutional capacity to enact fast mitigation, in particular in countries with currently low government effectiveness scores, an even higher overshoot will soon become inevitable. Our study does not imply that the 1.5 °C target needs to be abandoned. Rather, it provides a nuanced picture of what needs to happen to peak temperatures at a minimal overshoot above 1.5 °C to decrease temperatures afterwards. However, given our focus on improved understanding of near- and medium-term feasibility constraints, we look only at the trajectories until peaking and do not discuss in detail strategies and trade-offs for temperature reductions after the peak[3].

The analysis does, however, make clear that to bring temperatures down to below 1.5 °C after such an overshoot, a substantial amount of several hundreds of Gt CO_2 per 0.1 °C of overshoot will need to be removed from the atmosphere. Reducing demand and increasing electrification, while not being sufficient alone to avoid overshoot, will be very helpful when it comes to reducing temperatures from such an overshoot, as reduced demand for energy services leaves more energy and materials available for carbon dioxide removal. This is particularly important in the presence of technological, geophysical and institutional constraints limiting the availability of bioenergy and CCS and their viability in certain regions.

Our study provides an innovative addition to the scenario literature in that it explicitly considers harmonized feasibility constraints along various dimensions. The results show that technological constraints are not the most critical concern for mitigation, given the latest acceleration of observed deployment in key mitigation technologies. Enabling factors such as reduced demand, especially in high-income regions, and faster demand-side transformation towards electrification can help to lower the achievable lowest peak temperatures for a given set of assumptions.

The most important dimension studied, however, is the institutional dimension. Our results show that explicit consideration of institutional constraints allows for delineating a plausible, though fuzzy, lower limit of peak temperature increase. The nuanced results show that both the assumptions on the relationship between government effectiveness and feasible mitigation ambition and the built-in model difference have an impact on results.

When looking at scenarios with enablers, it is important to keep in mind that we have not considered the potential economic or political costs of faster technological transformation and reduced demand in high governance regions nor have we considered an explicit feedback of enablers on allowing for faster relaxation of the institutional constraints.

While our work goes beyond existing assessments of feasibility considerations, more work can be done to look at the dynamics between different aspects of feasibility and to link this work with frameworks of probabilistic policy outcomes[45]. Including feasibility assessments of methane abatement[46–49] will also be important for a more complete understanding of the feasibility of different peak temperatures as will be studies that link the general approach presented here with a scenario set-up based on detailed policy packages[16] instead of generic carbon pricing. A robust insight from this work, however, is that focusing on cost effectiveness without consideration of institutional feasibility and regional differentiation leads to important biases in benchmark scenarios. Our approach has been to identify scenarios that qualitatively move towards higher feasibility as an important innovation, helping to fill the scenario space and creating a bridge between pure cost-optimal benchmark scenarios and pure bottom-up prospective scenarios[50–52].

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-024-02073-4.

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Methods

Motivation for the chosen scenario set-up

The latest IPCC assessment report AR6[6] included an analysis of the feasibility of mitigation pathways, and we here use the same five dimensions (Fig. 1). On the basis of the results of the IPCC analysis (Fig. 3.43 in Riahi et al.[6]), we put the largest emphasis on the Institutional dimension, which the analysis found to be of highest concern. We combine the Geophysical and Technological dimensions, which the IPCC analysis found to exhibit medium concern levels. The economic dimension is used as the diagnostic dimension, as this is kept unconstrained in the case of the 1,000 Gt CO_2 scenarios (below), though economic differentiation also is inherent to our treatment of the institutional dimension via the carbon price constraints. As the IPCC found that socio-cultural concerns are lowest across available mitigation scenarios (driven partly by limited explicit exploration of this dimension), we here use this dimension to explore a key enabling mechanism: assumptions on lowering energy demand and a faster demand transformation towards electrification (which both increase the concern level in the socio-cultural dimension) can reduce pressure across the other dimensions to arrive at overall more balanced levels of feasibility concerns (Fig. 2).

Scenario set-up

For the purpose of understanding the impact of feasibility assumptions on scenario characteristics and the lower level of achievable peak temperature, we run a protocol of 20 harmonized scenarios across eight global integrated assessment models (model descriptions of the used IAMs in Riahi et al.[4], overview table of scenarios in Supplementary Table 1). The protocol differentiates between two different peak temperature objectives and six different assumptions about feasibility.

Net-zero carbon budgets

In terms of peak temperature objective, one set of scenarios constrains the net-zero CO_2 budget[3,4] (from all sectors) from 2018 until the year of net-zero CO_2 to 1,000 Gt, which corresponds to a slightly higher than 66% likelihood of limiting peak warming to below 2 °C based on the latest science on carbon budget[10]. The other set aims to constrain the net-zero CO_2 budget to 550 Gt, or the lowest possible value in case that this is not possible given the models' default constraints, or any of the dedicated feasibility assumptions in the respective scenarios. All models implement equivalent mitigation ambition for non-CO_2 greenhouse gases, but we do not vary the feasibility assumptions around non-CO_2 abatement explicitly (however, we do note that non-CO_2 abatement is important for temperature outcomes[22]). We thus translate net-zero CO_2 budget results into likelihoods of peak warming assuming a constant uncertainty of non-CO_2 impacts across scenarios and models. The scenarios are constructed such that after reaching net zero, global CO_2 emissions stay at net zero until the end of the modelling period (2100). This makes sure that net-zero budgets are aligned to 1,000 Gt CO_2 across models in the first case and provides a harmonized assumption for the evolution of mitigation ambition after net zero in the latter case. However, this is not meant to imply that net-zero CO_2 emissions and a mere stabilization of temperature at the peak level is desirable. Our study intends to inform the debate on feasible trajectories towards peak temperature but not about desirable pathways afterwards, including an eventual return to lower temperatures through sustained net-negative CO_2 emissions after passing net zero[3]. In a previous study comparing scenarios with and without net-negative CO_2 emissions after net zero, it was shown that there is no relevant impact of this choice on near-term mitigation trajectories[53].

Feasibility assumptions

In terms of feasibility assumption, we consider 14 different variants, made up by six main variants explained in the following section, and the two alternative sensitivity settings for the institutional setting explained in the next paragraph (only for the highest ambition carbon budget): first, in the *Cost-effective* setting, globally harmonized carbon prices increasing at the model's default rate are used for meeting the net-zero targets, and only model-default constraints are used. Second, a *Tech* constraint case considers technology-specific feasibility concerns for all energy supply technologies and for bioenergy and carbon capture and storage (CCS)[54]. In the case of wind, solar, nuclear and gas electricity generation and CCS, the annual rate of deployment (ramp up) is constrained, whereas bioenergy is subject to a limit of 100 EJ per year (ref. 55). Third, scenarios with *Institutional* constraints assume regionally differentiated[17] and time-varying maximum carbon prices and emissions-reduction rates, based on empirical work and government effectiveness indicators from the World Bank[33,56] (more details below). Fourth, the previous two constraints are combined in the *Tech and Institutional* setting. Fifth, the *Enablers and Institutional* case considers the combination of the institutional regional differentiation of maximum decarbonization rates with optimistic assumptions on socio-cultural enablers for demand-side electrification[38] and reduced energy demand with a focus on regions with high per capita demand[57]. Finally, the sixth variant, *Tech and Enablers and Institutional*, explores the combination of the institutional and technical constraints with the socio-cultural enablers.

Implementation of institutional constraint

Whereas there are many possible ways to measure the competence of governments, we focus on the 'government effectiveness' indicator, which is one of the six indicators proposed by the World Bank to measure governance and institutional quality. The specific indicator assesses the quality of policy formulation and implementation of a given country—that is, the ability of government to elaborate, implement and enforce policies[58] and has been estimated along Shared Socio Economic Pathways[59] for all countries until the end of the century, using projected levels of GDP per capita, gender equality and education levels[33]. Government effectiveness is a result of certain governance and institutional characteristics to which we, for simplicity, refer to as 'institutional capacity' given that many governance structures are driven by institutions.

This government effectiveness indicator is calculated for each model region as a weighted average across each region's countries (which typically are clustered based on geographical proximity and socio-economic similarity) with population as weight and then linked to maximum carbon prices (both relative to the highest regional carbon price and in absolute terms) and emissions-reduction constraints in the default and pessimistic setting. The carbon price is used as a stylized representation of climate policy. In the real world, the various fiscal and non-fiscal policy instruments to reduce emissions would not necessarily take the form of an explicit pricing on carbon emissions but could also be achieved via regulation, subsidies or a combination of carbon pricing and other measures addressing mitigation options with abatement costs up to the carbon price level used in the models. Whereas various studies with IAMs explore more detailed policy packages[16,60], we here use only carbon prices to have a more manageable transparent and easier reproducible harmonized scenario design across models. For the same reason, we use the same carbon price threshold levels across models, despite models differing in the price level required to reach a given target. Carbon prices, however, vary by model given that they are calculated based on the regionally average governance indicator using population as weight, and models' regional resolution differ.

The four feasibility variants including the institutional constraints for the lowest carbon budget setting are further analysed in three different sensitivity settings: the *default* setting of both differentiated and constrained carbon prices and maximum emissions reductions, both as a function of dynamically improving governance scores; the more *optimistic* setting of only differentiated and constrained carbon prices based on dynamically improving governance scores; and the *pessimistic* setting of both differentiated and constrained carbon prices and maximum emissions reductions based on governance scores frozen at the 2020 level (Fig. 1).

Data availability

The underlying data are available via Zenodo at https://doi.org/10.5281/zenodo.11562539 (ref. 61). All scenarios are made accessible online also via the ENGAGE Scenario Portal at https://data.ece.iiasa.ac.at/engage.

Code availability

The models are documented on the common integrated assessment model documentation website (https://www.iamcdocumentation.eu/index.php/IAMC_wiki), and several have been published as open source code (for example, REMIND, https://github.com/remindmodel/remind; MESSAGE, https://github.com/iiasa/message_ix). A repository for the source code of the figures is available via Github at https://github.com/christophbertram/Feasibility-scenario-analysis.

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Author contributions

C.B., E.B. and K.R. designed the study with input by L.D., E.K., G.L., B.v.R., R.S., D.v.V. and Z.V.; E.B. and C.B. prepared the governance input data for the IAMs; C.B., E.B., L.D., B.v.R., L.A.R., L.B.B., H.-S.d.B., V.D., F.F., D.F., O.F., S.F., K.K., V.K., R.M., P.R., R.S., D.S., I.T. and Z.V. produced the IAM scenario results; R.C., G.I. and N.H. provided a review of results and framing; R.D.L. and J.R. provided temperature probabilities as a function of carbon budgets; C.B. performed the data analysis and produced the plots with input by E.B. and L.D.; C.B. wrote the first draft and all authors contributed to writing the paper.

Competing interests

The authors declare no competing interests.

Additional information

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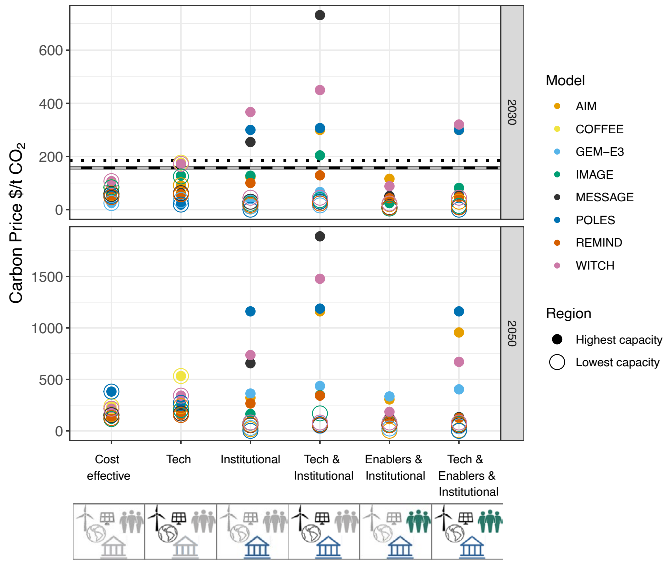

Extended Data Fig. 1 | Absolute carbon prices in the highest and lowest capacity regions in the 1000 Gt scenarios in 2030 (top panel) and 2050 (bottom panel). The horizontal lines in the upper panel show the median 2020 social cost of carbon estimates in grey dashed, black solid and black dotted lines from Rennert et al.[41], EPA[42], and Moore et al.[43] respectively. Please note that for highest capacity regions the POLES datapoint for 2030 in the "Tech & Enablers & Institutional" scenario covers the datapoint for AIM at the same value below. Furthermore the REMIND datapoint for 2050 in the "Tech & Enablers & Institutional" scenario partially covers the MESSAGE and IMAGE datapoints at very similar values below.

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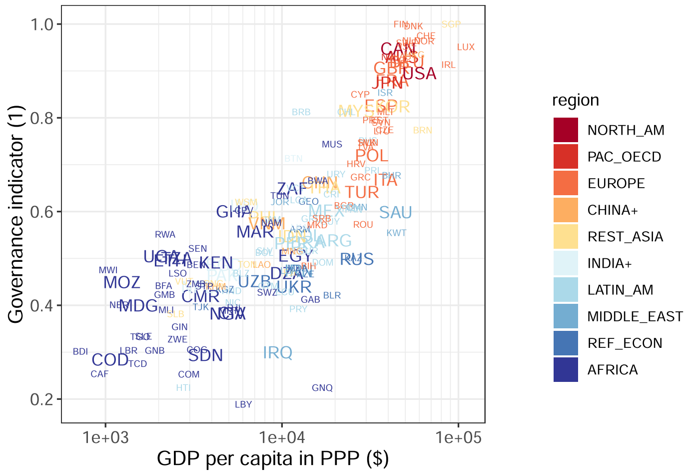

Extended Data Fig. 2 | Relationship between governance indicators from Andrijevic et al.[33]**, and GDP per capita (in PPP).** The countries with a population of more than 25 million are shown in large ISO code labels, while the smaller ones are shown in semi-transparent, smaller labels. Note the logarithmic x-Axis.

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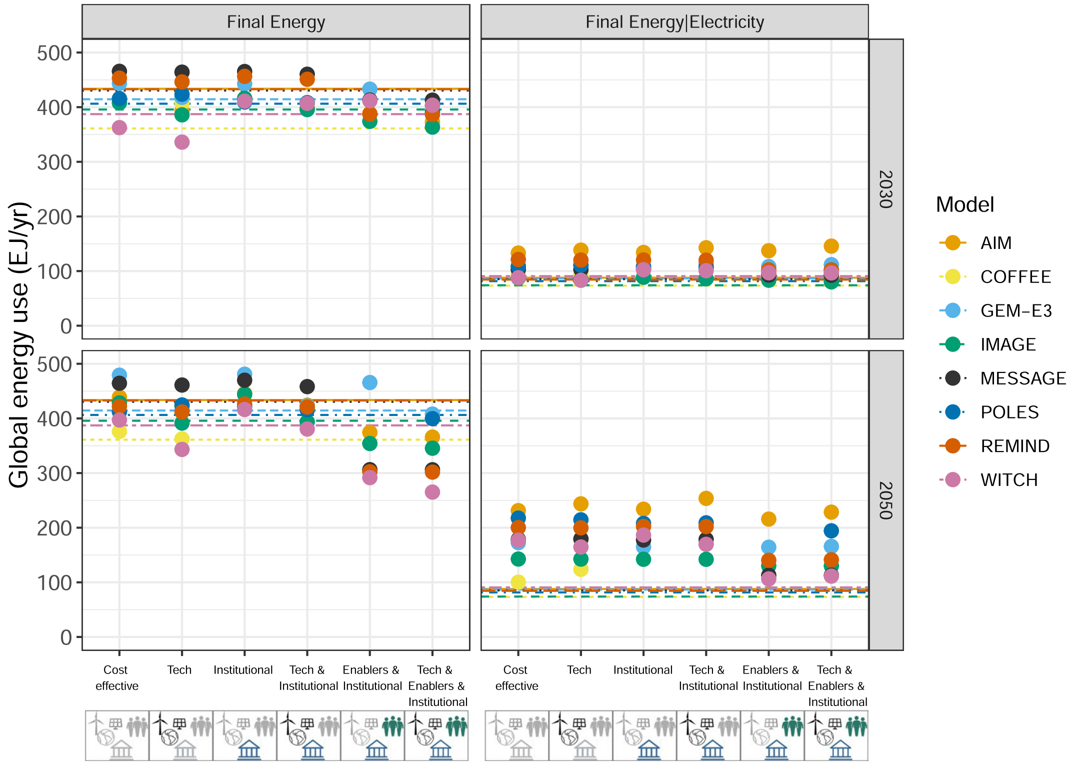

Extended Data Fig. 3 | Global final energy use in 2030 and 2050. The dashed lines in the background show the model's 2020 values (which due to different calibration routines do not all coincide).