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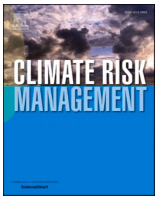

Literature-informed likelihoods of future emissions and temperatures

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ABSTRACT

How high should we build a dyke today, knowing that it will serve for more than 50 years? This depends on the probability distribution of future temperatures. We review the literature on estimates of future emissions for current/stated policy scenarios and current pledge scenarios. Reviewing expert elicitations, abatement costs of scenarios, learning rates of technologies, fossil fuel supply side dynamics and geoengineering, we argue that scenarios with emissions largely beyond current/stated policy scenarios and largely below current pledge scenarios are relatively unlikely. Based on this, we develop a literature-informed evaluation of the likelihoods of future temperature for use in Value at Risk stress tests in 2030, 2050 and 2100.

1. Introduction

How likely will warming exceed 3 °C in 2100? And how likely will we stay below 2 °C? Many studies answer this question conditional on a given emission or policy scenario. This article aims to obtain a single, unconditional probability distribution for future temperatures. We review the literature on how likely different emission scenarios are and use this to develop a literature-informed evaluation of the likelihoods of future temperature outcomes.[1] To do so, all sources of uncertainty matter, not only climate sensitivities, but also future policies, technological developments, international agreements, etc.

This is important because for long-term adaptation strategies, long-term investing, insurance, and many other applications, a single, unconditional probability distribution of future temperatures is required. For example, long-term investors and insurers need to analysis the impact of a range of climate scenarios, each with their probability, to forecast probability-weighted mean outcomes (ABRDN, 2021; Aviva, 2022) Whilst these assessments are necessarily subjective, they also need to be in line with the academic literature. Therefore, this article provides the first literature review that is structured around unconditional future likelihoods of temperatures.

The question of whether to assign likelihoods to different emission scenarios has been a matter of on-going debate (Pedersen et al., 2022). On the one hand, it was argued that emission scenarios could not be represented by probabilities because future emissions fall into the category of "unknowable" knowledge, which depends on subjective judgments of unpredictable socioeconomic developments (Dessai & Hulme, 2004). On the other hand, scholars argued that scenario-building always requires implicit judgements about

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[1] In this regard the paper is a hybrid including both review and research elements.

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Table 1
The increase in global mean surface temperature compared to the preindustrial period (average between 1850–1900) for the IPCC pathways (Masson-Delmotte et al., 2021). RCP3.4 and 6.0 mean temperatures are from Riahi et al. (2017) and their uncertainty intervals are interpolated (not reported by the IPCC).

Scenario	2021–2040 Best estimate (°C)	5–95 % likely range (°C)	2041–2060 Best estimate (°C)	5–95 % likely range (°C)	2081–2100 Best estimate (°C)	5–95 % likely range (°C)
SSP1-1.9	1.5	1.2 to 1.7	1.6	1.2 to 2.0	1.4	1.0 to 1.8
SSP1-2.6	1.5	1.2 to 1.8	1.7	1.3 to 2.2	1.8	1.3 to 2.4
SSP4-3.4	1.5	1.2 to 1.8	1.9	1.5 to 2.4	2.2	1.7 to 3.0
SSP2-4.5	1.5	1.2 to 1.8	2.0	1.6 to 2.5	2.7	2.1 to 3.5
SSP4- 6.0	1.5	1.2 to 1.8	2.1	1.7 to 2.6	3.1	2.4 to 4.0
SSP3-7.0	1.5	1.2 to 1.8	2.1	1.7 to 2.6	3.6	2.8 to 4.6
SSP5-8.5	1.6	1.3 to 1.9	2.4	1.9 to 3.0	4.4	3.3 to 5.7

likelihoods. "The literature on scenarios often aims to make a sharp distinction between scenarios and forecasts or projections; for example, it is asserted that scenarios are judged by their 'feasibility' or 'plausibility' rather than their likelihood. We cannot find any sensible interpretation of these terms other than as synonyms for relative subjective probability. Absent a supernatural ability to foresee the future, what could be meant by a statement that one scenario is feasible and another infeasible but that the first is (subjectively) more probable than the second?[2]" (Morgan & Keith, 2008). Schneider (2001) warned early on that by not attaching probabilities to scenarios, policy makers would tend to interpret them as equally likely.

We will not focus on this philosophical debate but start from the simple fact that policymakers and business need temperature likelihoods to make forward-looking decisions. Governments are already planning adaptation infrastructure and need likelihoods of warming to set priorities. Furthermore, corporations, banks and insurers increasingly need to assess the likelihoods of different future temperatures in order to report how their business strategy incorporates climate-related risks and investment opportunities. Often these reporting requirements have become mandatory.

We will also provide a sensitivity analysis to acknowledge the unavoidable ambiguity regarding true unconditional probability distribution. The question makes more sense today than 10 years ago, because we will show that both very low and very high levels of warming have become much less likely. The likelihood of staying below 1.5 °C has become very low due to high emissions in the past decade. Very high emission scenarios have also become very unlikely because the costs of renewables have decreased much faster than expected and renewables now outcompete coal in certain countries, even without policy. Coal consumption has stagnated since 2013 (IEA, 2022).

The technological, political and socio-economic drivers of future temperatures are very hard to predict. The probability distribution of future events is not known and it is not possible to make an unbiased, consistent estimate as one would make for short term weather forecasts. For weather forecasting, assuming a single 'data generating process', which drives both past and future weather, will result in an unbiased and consistent estimate of the future mean, variance and higher moments. Estimating climate model uncertainty for a given emission scenario is already harder. Since the 1990 s the IPCC has released probability distributions of future temperatures for different emission scenarios. However, unlike weather forecasts where the difference between the forecasts and the observed weather allows us to assess confidence intervals, the models try to predict a world that has never existed, using the laws of physics, chemistry and biology as well as paleoclimate information, to extrapolate our current understanding of the planet into unobserved territory. The uncertainty intervals are neither unbiased nor consistent estimates in an econometric sense, yet they are very important for governments, businesses and academic work.

Estimating the probability distribution of future emission scenarios is even harder. Because it requires forecasting future policies, future international agreements and technological change over many decades. Also, not only are probabilities hard to estimate, the set of possible outcomes is not known. There may be political or technological developments in the coming century that we are not able to imagine today. This is known as deep uncertainty (Kay and King, 2020; Workman et al., 2021). The possibility of certain unknown tipping points in the climate system also contributes to deep uncertainty. This will lead to a given level of subjectivity. The aim of this article is to provide the relevant literature that will allow governments, businesses and citizens to form an informed, yet unavoidably subjective, view on future likelihoods of emissions and temperatures.

There is a large literature on decision theory in the presence of deep uncertainty. Several methods focus on ambiguity aversion and add a layer of 'prudence' to correct for model misspecification and imperfect knowledge about stochastic processes (Barnett, Brock and Hansen, 2020; Berger and Marinacci, 2020; Jensen and Traeger, 2022). However, even these models start from a 'best guess' for model parameters and their stochastic properties. Similarly, Bayesian approaches start from a 'prior' probability distribution, to be updated when new information becomes available. The aim of this article is to give guidance on such an informed best-guess or a Bayesian prior distribution of future temperatures.

Several recent papers give an overview of emission estimates of current or stated policy scenarios and current pledge scenarios (Hausfather and Moore, 2022; Meinshausen et al., 2022; Raimi et al., 2022). We give a more detailed overview of 28 underlying scenarios in 13 studies between 2021 and June 2023. We also discuss how likely we will see emissions below or above these scenarios building on expert elicitation (Ho et al., 2019; Rennert *et al.*, 2022), abatement costs (Myles et al., 2018; NGFS, 2020), learning rates

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[2] Jewel and Cherp (2023) discuss the nuances between feasibility and probability.

Table 2
Description of current policy scenarios. None of the scenarios include zero emission pledges, some scenarios include NDC's for 2030.

Source	Year	Name	GHG	Emissions 2019–2050	Temperature in 2100	Description
IPCC WGIII(Shukla et al., 2022)	2021	Implemented policies	All	+9%		Pathways with projected near-term GHG emissions in line with policies implemented until the end of 2020 and extended with comparable ambition levels beyond 2030.
IEA World Energy Outlook(IEA, 2021)	2021	Stated Policies Scenario	CO2 from energy and industry	−6%	2.6 °C	Current policy settings based on a sector-by-sector assessment of the specific policies that are in place, as well as those that have been announced by governments around the world.
UNEP Emissions Gap Report(UNEP, 2021)	2021	Current Policy Scenario	All	−13 %	2.7 °C (P66 = 2.8 °C)	Projections of the current policies scenario assume that no additional mitigation policies and measures are taken beyond those adopted and/or implemented.
Climate Action Tracker (Climate Action Tracker, 2021)	2022	Policies and actions	All	−10 % to + 10 %	2.7 °C	Real world action based on current policies.
Meinshausen *et al.*(Meinshausen et al., 2022)	2022	2030 NDC extrapolation	All without LULUCF	−15 % to + 13 %	2.2–3 °C	Extend 2025–2030 growth or reduction rates until 2050, equal-quantile-walk thereafter. 2.2 °C for high ambition + full implementation + hot air excluded (commitments exceeding current emissions set to current emissions). 3 °C for Low ambition, unconditional commitments only and hot air included.
Rogelj *et al.*(Rogelj et al., 2023)	2023	Current policies	All	−50 % to −3%	2.6 °C	Considers only current policies, disregarding NDCs as well as net-zero and other long-term targets.
Sognnaes *et al.*(Sognnaes et al., 2021)	2021	Current policies /NDC's	CO2 from energy	−28 % to + 21 %		Includes NDC's from 2020, before the stricter commitments in 2021 and COP26. Large range of outcomes, mainly depending on the Integrated Assessment Model. After 2030 extrapolated growth rate of CO2/GDP or carbon price/GDP.
Morris *et al.*(Morris et al., 2022)	2021	Growing pressures	All	+2%	2.8 °C	A scenario that carefully considers emission-reduction trends and actions that are likely in the future, absent globally coordinated mitigation effort. Our scenario considers growing pressures from society and future technology trends that steer the energy system away from fossil fuels and captures current and expected future momentum across different drivers to reduce emissions and fossil fuel use…We do not impose global carbon pricing."
Ou *et al.*(Ou et al., 2021)	2021	Current policies	CO2 from energy and industry.	−3%	2.6 °C	Current policies assumes continuation of current sectoral and national policies until 2030 and a constant decarbonisation rate thereafter.
BP Energy Outlook(BP, 2022)	2022	New Momentum	CO2 and methane from energy and industry	–23 %		Least ambitious scenario of three scenarios which "explore the range of possible outcomes" and "are intended to encompass a significant range of the possible outcomes for the energy system out to 2050".
Shell Energy Transformation Scenarios(Shell, 2021)	2021	Islands/waves	CO2 from energy and industry.	−10 to −12 %	2.3 °C-2.5 °C	Islands corresponds to late and slow decarbonisation, with frictions in international trade and collaboration, stagnating growth and where the Paris climate process unravels. Nations are focused on their own short-term economic outcomes and remain dependent on cheap fossil energy for a prolonged period, and global emissions decline only slowly. Waves corresponds to late, but fast decarbonization, with net-zero emissions around 2100.
ExxonMobil Outlook for Energy(	2021		CO2 from energy	−15 %		There is only one scenario, defined as most likely outcome.

(*continued on next page*)

Table 2 (*continued*)

Source	Year	Name	GHG	Emissions 2019–2050	Temperature in 2100	Description
ExxonMobil, 2021)						
McKinsey Global Energy Perspective (McKinsey, 2022)	2022	Current Trajectory	Net CO2 from energy.	−58 %	2.4 °C	Current trajectory of renewables cost decline continues, however active policies currently remain insufficient to close gap to ambition. Implicit carbon price in 2030–2050 55–130 €/tCO2.
RFF, (Rennert *et al.* 2022)(Rennert et al., 2021)	2022	RFF Social Cost of Carbon Initiative	All CO2 (Gross, without geological storage)	−8%	3 °C	Not a current policy scenario, but a probabilistic emissions projection, using a combination of statistical modelling and expert elicitation. Based on 10 interviews with experts, weighted by their performance on known quantities, each lasting 2 h, July-August 2021. Experts estimated probabilistic ranges of future emissions. The scenarios are framed as Evolving Policies, which incorporates views about changes in technology, fuel use, and other conditions, and consistent with the expert's views on the evolution of future policy.

(Shukla et al., 2022), bottom-up cost predictions of backstop technologies, fossil fuel supply side dynamics (McGlade and Ekins, 2015), perceptions of current negotiators (Kornek et al., 2020), the likelihood of solar radiation management (Aldy et al., 2021), etc.

We organise the paper around the stylised emission scenarios from the 6th IPCC WGI report (Masson-Delmotte et al., 2021). The names of these scenarios have two components, combining a Shared Socio-economic Pathway (SSP), representing the socio-economic hypotheses underlying the scenario and a Representative Concentration Pathway (RCP). The number of the RCP indicates the climate forcing (extra energy in Joules per m^2 per second) by the end of the century. The IPCC 6th assessment report uses five main reference scenarios. We also add two other 'secondary' reference scenarios, i.e. SSP4-3.4 and SSP4-6.0. Each scenario represents a precise trajectory of emissions until 2100. We will use the RCP numbers 1.9, 2.6, 3.4, 4.5, 6.0, 7.0, and 8.5 as shorthand for the scenarios. Table 1 gives an overview of the estimated temperatures associated with each of the seven emission scenarios.

We will argue that current/stated policy scenarios lead to emissions in between RCP3.4 and RCP4.5 (Section 2) and that current pledge scenarios, where countries honour their zero emission pledges made at COP26, are close to RCP2.6 (Section 3). Section 4 will argue that scenarios that go beyond the current pledges are relatively unlikely (10–20 % likelihood for RCP1.9). Similarly, section 5 argues that scenarios exceeding current/stated policy emissions are again relatively unlikely (10–20 % total likelihood for RCP6.0, 7.0 and 8.5). Section 6 summarizes the likelihood of emission scenarios derived from the literature review in preceding sections. Section 7 then uses these emission scenarios' likelihoods to generate an overall probability distribution for temperature along with a sensitivity analysis. Section 8 concludes with a discussion on what actions could affect the likelihood of low emission scenarios in the future.

2. Current/stated policies scenarios

What is the most likely outcome if no new climate policy is added from 2022 onwards?

Table 2 and Fig. 1A give an overview of 14 studies estimating future emissions and temperature under current/stated policy scenarios or scenarios that are broadly in line with current policies. Definitions of current/stated policy scenarios vary slightly. For example, the IEA develops a Stated Policies Scenario, "which reflects current policy settings based on a sector-by-sector assessment of the specific policies that are in place, as well as those that have been announced by governments around the world." Some of the scenarios are based on Nationally Determined Contributions (NDC's) until 2030 with a constant decarbonization rate thereafter (Sognnaes et al., 2021; Meinshausen et al., 2022). Morris et al. (2022) disentangle the different socioeconomic drivers that are likely without further policies, and develop "a scenario that carefully considers emission-reduction trends and actions that are likely in the future, absent globally coordinated mitigation effort. Our scenario considers growing pressures from society and future technology trends that steer the energy system away from fossil fuels and captures current and expected future momentum across different drivers to reduce emissions and fossil fuel use…We do not impose global carbon pricing." We also report the 'slow and late' abatement scenarios from BP, Shell, and McKinsey based on a pessimistic view of additional policy. None of the current/stated policy scenarios include the zero-emission pledges and most of the scenarios only include NDC's by 2030 to the extent that the specific policies to obtain them are announced. When NDC's are considered, they are NDC's from before COP26. Between October 2021 and October 2022, NDC

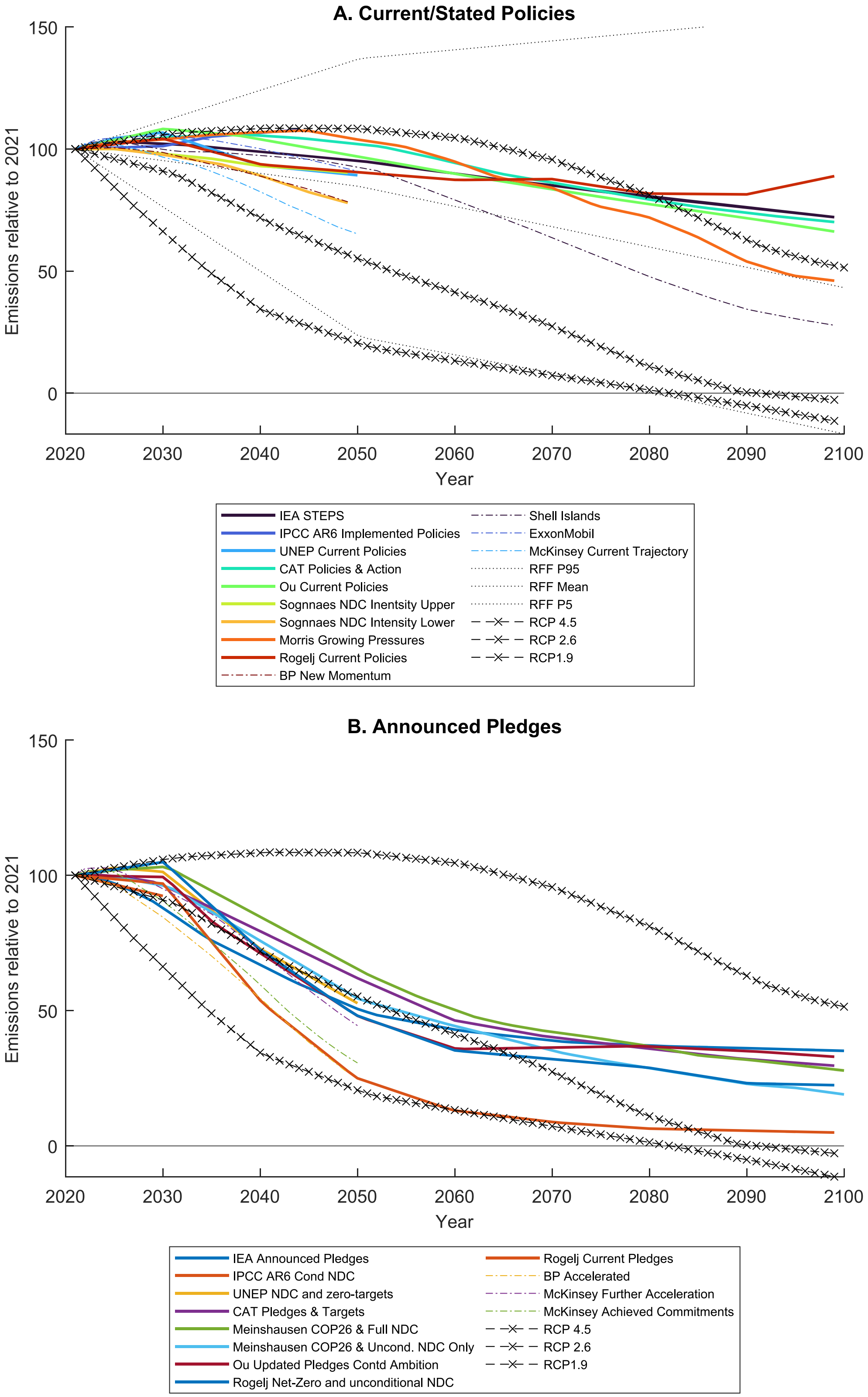

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Fig. 1. Emissions relative to 2021 of total greenhouse gas emissions or CO2 emissions in Current/Stated Policy scenarios (A) and Announced Pledge scenarios (B). The dotted lines are expert estimates which include future policy changes (RFF, Rennert *et al.*, 2022). As a benchmark, cross-marked lines show three RCP scenarios. Table 2 and 3 give more information on the scenarios. The Online Resource 2 contains the underlying data on absolute emissions.

emissions for 2030 were reduced by 5 % (UNFCCC, 2022).[3]

As shown in Table 2 the current policy scenarios estimate emissions in 2050 to be in between an increase of 21 % and decrease of 28 %. Expected temperatures in 2100 are between 2.2 °C and 3 °C, approximately between the RCP3.4 (2.2 °C) and RCP4.5 (2.7 °C) scenarios.

Emissions of current policy projections have been revised downwards over the last 5 years. The cost of renewables has decreased much faster than anticipated. "From 2010 to 2019, there have been sustained decreases in the unit costs of solar energy (85 %), wind energy (55 %), and lithium-ion batteries (85 %), and large increases in their deployment, e.g., $>10 \times$ for solar and $> 100 \times$ for electric vehicles (EVs)" (Shukla et al., 2022). The rapid cost decline of solar, wind and electricity storage led to a decrease in the future use of coal, which has been the dominant fuel for electricity in the past. Coal consumption has stagnated since 2013 and whereas the IEA expected coal to increase over the coming decades, it now projects a 25 % decline by 2050 under current policies. The development of cheap shale gas has further reduced the prospects of coal. Similarly for oil, the rapid cost decline of batteries has decreased future demand of oil. The IEA now expects stagnant oil consumption from 2030 onwards under stated policies.

Policies have also become more stringent over the last 5 years. The carbon price in the European Union Emission Trading Scheme increased from 5€/tCO2 in 2017 to over 80€/tCO2 in 2023. China started the world's largest emission trading scheme in 2021, regulating the power sector. After the election of President Biden, the US re-joined the Paris agreement. The Inevitable Policy Response (IPR, 2021), a policy analysis, also increased its climate policy forecast.

3. Announced pledges scenarios

Fig. 1B and Table 3 give an overview of Announced Pledge scenarios. The IEA defines their Announced Pledges Scenario (APS) as a scenario "which assumes that all climate commitments made by governments around the world, including the new Nationally Determined Contributions (NDCs) and longer term net zero targets, will be met in full and on time." The scenario assumes that on top of current policies, new policies are added to go to zero emissions in all countries that have pledged to do so. Table 3 gives an overview of five estimates of announced pledges and four other estimates with high policy ambition. Emissions in 2050 are assumed to be reduced by 38 % to 54 %.[4] As pledges have been updated between 2021 and 2023, the announced pledge scenarios have become more ambitious. The earlier estimates lead to warming between 2.1 °C and 2.2 °C. Meinshausen et al. (2022), include the Indian commitment made during COP 26. Depending on conditional commitments, they estimate 2 °C to 1.9 °C warming in 2100. The latest study in our sample is Rogelj et al. (2023), including commitments until late 2022. Depending on conditional commitments, they estimate an emission reduction of 58 % to 63 % by 2050, and warming of 1.9 °C and 1.7 °C in 2100. This means that, the most recent announced pledges scenarios have emissions slightly below SSP1-RCP2.6.

4. How credible are the new commitments?

Victor et al. (2022) conducted a survey of 599 negotiators and 230 scientists at COP26 in 2021 regarding the credibility of NDC's. Participants rated their home country's expected compliance with its NDC at around 3.5 on a Likert-scale, from 1 (not confident at all) to 5 (very confident). Confidence was slightly higher for the European Union (3.7), and much lower for North America (2.3), slightly higher for negotiators than for scientists and higher for countries perceived as ambitious. Experts were more pessimistic when they evaluated credibility of the NDC's of other countries. Scores on other countries' ambition are below 3, with the exception of the European Union (3.8). USA, Brazil, Saudi Arabia and Russia are perceived as least credible, with scores below 2.5 (Victor et al., 2022).

Interestingly, for non-OECD countries (with 80 % of future emissions), when asked about the most important motivations to comply, "economic growth opportunities" were perceived as the most common motivation (75 % of experts). Abatement will indeed lead to green technological improvements. However, it may also reduce the ambition of future NDC's where countries observe that stringent abatement is costly.

Rogelj et al. (2023) argue that many zero targets have low credibility, because they are not legally binding, not associated with policy plans and/or not in line with current policy projections. They argue that these criteria are met by a minority of countries (EU, New Zealand, UK, see Table SM5).

Updates in climate policy ambition between 2019 and 2022 have occurred at the same time as changes in the social and technological environment. There have been protest movements such as the strikes for the climate with Greta Thunberg in Europe. Covid has demonstrated that we are vulnerable to disasters at a global level. There have been technological shifts, with Tesla's market value

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[3] The NGFS (2021) includes two scenarios named 'current policy' and 'Nationally Determined Contributions (NDC)', with high emissions and temperatures (2.6°C and 3°C respectively). Both scenarios are a combination of 1) stated polices or NDC's, 2) slow technological change and 3) low carbon dioxide removal, as part of the 'hot house world' family of scenarios. Since it is a combination of adverse factors, we do not include them with the other scenarios.

[4] BP has a scenario with emission reductions of −75% but it is not defined as announced pledge scenario.

Table 3
Description of Announced Pledges scenarios.

Source	Year	Name	GHG	Emissions 2019—2050	Temperature in 2100	Description
IPCC WGIII(Shukla et al., 2022)	2021	NDC's conditional	All	−10 % in 2030		NDC's prior to COP26 including conditional elements.
IEA Energy Outlook(IEA, 2021)	2021	Announced Pledges Scenario	CO2 from energy and industry	−45 %	2.1 °C	Includes net-zero pledges but not those made during COP26.
UNEP Emissions Gap Report(UNEP, 2021)	2021	Unconditional NDC and Pledge scenario with net zero targets	All	−51 %	2.1 °C (P66 = 2.2 °C)	Includes net-zero pledges but not those made during COP26.
Climate Action Tracker(Climate Action Tracker, 2021)	2022	Pledges & Targets	All	−41 %	2.1 °C	Includes net-zero pledges but not those made during COP26.
Meinshausen *et al.*(Meinshausen et al., 2022)	2022	NDC's + LT targets	All without LULUCF	−38 % to −49 %	1.9 °C-2 °C	All NDC's and zero-emission targets by mid-November 2021 + India during COP26.
Ou *et al.*(Ou et al., 2021)	2021	Updated Pledges, continued ambition	CO2 from energy and industry.	−54 %	2.2 °C	Updated pledges and long term strategies (zero emission targets) are achieved. If long term strategy is absent, the decarbonization rate is identical to 2015–2030 and minimum −2%/year.
Rogelj *et al.*(Rogelj et al., 2023)	2023	All net zero targets	All	−50 %	1.9 °C	All net zero targets are met. When "lowest" and "low" confidence targets are excluded, expected temperatures are 2 °C and 2.4 °C respectively.
Rogelj *et al.*(Rogelj et al., 2023)	2023	Current Pledges	All	−80 %	1.7 °C	All net zero targets plus all conditional NDC's are met.
BP Energy Outlook (BP, 2022)	2022	Accelerated		−75 %		Middle scenario of three scenarios which "explore the range of possible outcomes".
McKinsey Global Energy Perspective(McKinsey, 2022)	2022	Further Acceleration	CO2 from energy	−40 %	1.9 °C	Further acceleration of transition driven by country-specific commitments, though financial and technological restraints remain. Implicit carbon price in 2030–2050 of 75-140€/tCO2.
McKinsey Global Energy Perspective(McKinsey, 2022)	2022	Achieved Commitments	CO2 from energy	−53 %	1.7 °C	Net-zero commitments achieved by leading countries through purposeful policies; followers transition at slower pace. Implicit carbon price in 2030–2050 100–180 €/tCO2.

almost exceeding the value of all other car makers put together. The US has re-joined the Paris agreement enabling meaningful international climate negotiations to continue.

It is however easy for governments to commit to long term targets, given that politicians can get away with not making the necessary decisions today while still claiming that the long-term goal remains. Governments may backload the effort, to an implausible degree. It is therefore important to assess how hard it will be in practice to meet the zero emission targets.

A first reason why these scenarios are challenging is that they require stranding of assets before their end of life or at least retrofitting these assets with technologies such as CCS. The IPCC estimates that currently existing electricity infrastructure will emit 300 GtCO2, and existing infrastructure in other sectors will emit 300 GtCO2 before its end of life (Shukla *et al.*, 2021). Currently proposed investments in coal will add another 97GtCO2 and investments in gas and oil will add a similar 92GtCO2 (IEA, 2021). So, existing and currently planned infrastructure will emit 847GtCO2, i.e., the entire emission budget to stay below 2 °C (890 GtCO2)(Masson-Delmotte et al., 2021). According to the IEA's Announced Pledge Scenario, yearly coal power plant retirements will increase from 25GW in the past decade to 49GW, 33GW and 30GW in the three coming decades. Initially these retirements will be predominantly in advanced economies. By contrast, by 2050, 95 % of these retirements will be in developing countries (IEA, 2021).

A second implementation challenge is the large upfront investments that are required. IEA's Announced Pledge Scenario requires an increase in investments in energy and energy efficiency of 120 % in the period 2026–2030, compared to 2016–2020.

Third, the transition may be quite costly. The Supplementary Information (Online Resource 1, SI 1) reports abatement costs for all the scenarios in the 1.5 °C IPCC report. Total abatement costs for all scenarios which stay below 2 °C are 3.1 % of world GDP in 2030 (interquartile range of 2.0 % to 3.9 %).[5] The marginal abatement cost, which corresponds to the carbon price if regulation is based on a price mechanism, is $119/tCO2 ($79-$231/tCO2). Moreover, most models do not take into account that marginal abatement costs will

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[5] These GDP figures just cover the cost of abatement. They do not take into account the cost of damages from increases in temperatures in these scenarios.

differ between countries and sectors, which will increase total costs. We are nowhere near these implicit abatement costs. As a result, current world emissions are larger than ever, increasing by 1.3 % per year between 2010 and 2019 (Masson-Delmotte et al., 2021). Although the pandemic led to the largest decrease in emissions ever, emissions in 2022 were similar than in 2019 (IEA, 2022).

It is important to note that there is academic disagreement regarding future abatement costs. Estimates of abatement costs have decreased over time, because the learning speed of green technologies has been repetedly underestimated in the past and some scholars argue that it is still underestimated today (Way et al., 2022). As a result, costs in the 6th IPCC assessment report are slightly smaller than the ones mentioned above (Shukla et al., 2022). The IPCC report is based on bottom-up models, using engineering estimates for future technologies. They typically include a large potential for abatement opportunities at zero cost (16 % of emissions in 2030). By contrast, economic top-down models assume that all abatement is costly, due to hidden costs, and barriers to investment, information, and behavioural change (see further). As a result, economic top-down models find higher abatement costs than the IPCC (Kotchen et al., 2023). Most empirical studies find no effect of (low) carbon prices on GDP (Metcalf and Stock, 2020; Venmans et al., 2020), whereas studies of other programs aimed at reducing emissions often find costs that are much larger than anticipated in engineering studies (Fowlie et al., 2018).

Instead of looking at costs, one can also investigate deployment trends. The diffusion of new technologies often follows an S-curve, growing exponentially at the start, reaching an inflexion point at top speed and gradually reaching a satiation point thereafter. Way et al. (2022) fit world-wide deployment of green technologies (PV, wind, batteries, and electrolysers) to such an S-curve and argue that current growth rates allow to go stay below 2 degrees. However, this is very sensitive to the assumption of where we currently are on the S curve. Cherp et al. (2021) fit the same S-curves for individual countries, including countries that are beyond the inflection point and find that countries' maximum growth rates are between 0.4 % and 1.1 %, which is insufficient to reach 1.5 °C to 2 °C warming.

The general picture is that the current pledges scenario (RCP 2.6) requires stranding of existing infrastructure, doubling of investments in energy and energy efficiency, and a median cost of 3 % of global GDP which could be much lower, but also much higher.

5. Scenarios which limit warming to 1.5 °C

How likely are emission scenarios which go beyond the current pledges, resembling the IPCC's RCP1.9 scenario, limiting warming to 1.5 °C with limited overshooting?

The IEA developed a Net zero emission (NZE) scenario, similar to RCP1.9, "which sets out a narrow but achievable pathway for the global energy sector to achieve net zero CO2 emissions by 2050." The scenario requires a quadrupling of energy investments over the next decade from 1 to 4 trillion USD per year (IEA, 2021). This represents 15 % of the world's total investment. However, the IEA estimates that 40 % of the emission gap between the Announced Pledges Scenario and the Net Zero Emission scenario can be closed with cost-effective investments. Although cost-effective measures are easier to realize than costly investments, we argue below that there are substantial barriers to these investments.

The largest room for cost-effective emission reductions is expansion of wind and solar, reducing the need for coal by 350 GW in developing countries, of which 200GW is currently planned or under construction (IEA, 2021). Note however that this is based on the hypothesis that wind and solar projects could be realized with a low cost of capital, similar to interest rates in the developed world. In reality, the cost of capital for wind projects in the global South is high (10 to 15 %) because investment in the global South is riskier, which makes wind more expensive. This means that wind is competitive in those markets if cheap loans can be made available. But cheap loans for risky projects boils down to an indirect subsidy by the lender (development bank or developing country). The same argument applies to the second most important lever for cost-effective emission reductions which is methane abatement in extractive industries (IEA, 2021). Again, most of these opportunities are situated in poor countries with limited climate policy and many hurdles to investment.

Even under a rapid ramping up of climate ambition there will still be a lot of emissions in the coming decade, because fossil fuel based capital creates large inertia in the economy. And stranding industrial assets is politically very difficult. For example, yearly coal power plant retirements in the IEA's Net Zero Emission scenario increase from 25GW in the past decade to 90GW, 60GW and 25GW in the three coming decades (IEA, 2021).

However, certain developments make 1.5 °C scenarios more likely. For example, future trade agreements which penalize countries for excessive emissions, may lead to a tipping point towards a low emission regime (Nordhaus, 2021). Also, some authors argue that the extent of technological change is underestimated and that it has the potential to reach a zero emission at no long term cost (Acemoglu et al., 2012; Way et al., 2022). RCP1.9 includes a large amount of negative emissions in the second half of the century. Biomass Energy with Carbon Capture and Storage (BECCS), Direct Air Carbon Capture and Storage (DACCS) and mineral weathering are the main negative emission technologies in forecasts. Although they are costly, they may benefit from large cost reductions as a result of technological change (Online Resource 1, SI 2).

The effect of other anthropogenic climate forcers on climate is ambiguous. The current warming due to greenhouse gases is estimated between 1 °C and 2 °C. And anthropogenic cooling, mainly due to aerosols, is estimated between 0 and 0.8 °C (Masson-Delmotte et al., 2021). Yet aerosols will decrease in the future, because they cause 4.2 million deaths per year (WHO, 2022), they are local, relatively cheap to avoid, short-lived and therefore they tend to decrease with economic growth. So, keeping warming below 1.5 °C may turn out to be very difficult, because we reduce other air pollution. The effect of aerosols can also go the other way. It is very cheap to add aerosols to the high atmosphere, a geoengineering technique which cools the earth. The main obstacles against solar radiation management are the poor understanding of side effects (large weather and storm patterns may be affected) and the difficulties in international coordination because damages and gains from climate change are unevenly distributed and countries have different stances on risks related to geo-engineering (Aldy et al., 2021).

The expert panel questioned by the RFF (2022) in July 2021, attributes a 5 % probability of exceeding the ambition of the RCP1.9 scenario. However, they were questioned in the summer of 2021. Since then, most countries in the world have committed to zero-emission targets, corresponding to a 75 % of reduction in emissions by 2050 and 1.7 °C warming in 2100 (Rogelj et al., 2023, scenario including conditional NDC's). For example, new NDC's with zero emission targets, mainly by Indonesia, China and India correspond to a reduction of 0.3 °C warming (Meinshausen et al., 2022). As a result, we will attach a larger likelihood to the RCP1.9 scenario.[6] This acknowledges criticism in the literature, arguing that the current integrated assessment models which project population, economic growth, technology development and policy over many decades can give an illusion of good foresight (Kay and King, 2020; Workman et al., 2021). For example, between 1960 and 1980, forecasting primary energy demand was crucial, given the oil crisis of the seventies. None of 12 most prominent forecasters included the observed value in 2000, which was much lower than expected (Morgan and Keith, 2008). One has to think about how accurate economists were 75 years ago (during World War II) at predicting population, GDP, technology and political systems of today's society. This acknowledgement of how hard it is to forecast many decades into the future also applies to high emissions scenarios which we discuss now.

6. Scenarios beyond 3 °C

What is the likelihood that current policies are reversed and that we end up on a trajectory of RCP6.0, RCP7.0 or RCP8.5?

No-policy scenarios are dynamic in nature. A no-policy scenario estimated in 2010 has more emissions than a no-policy scenario estimated today because the past policies affect the cost of future technologies. Between 2010 and 2019, the unit costs of solar energy, wind energy and lithium-ion batteries have been reduced by 85 %, 55 % and 85 % respectively (Shukla et al., 2022). Even if current policies are reversed, these cost reductions will remain. Therefore, RCP6.0, RCP7.0 or RCP8.5, conceived a decade ago as no-policy scenarios, have become less likely even if current policies would be reversed.

When established around 2010, RCP8.5 was based on larger economic growth, a slower decrease of carbon intensity and aggressive use of coal compared to the past. Coal consumption would be 5 times larger in 2100 compared to today.

Burgess et al. (2020) analyse the discrepancy between the IPCC's reference scenarios on the one hand and a combination of observations and the IEA on the other hand. They show that the IPCC scenarios (AR5) have overestimated emissions, mainly due to an overestimation of GDP growth[7] and the assumption of an increasing trend in coal consumption. Most IPCC (AR5) and SSP baseline scenarios project futures in which carbon intensity would not decline in the absence of climate policies, whereas experience of the past decade suggests that factors beyond climate policy may motivate carbon-intensity declines. Particularly, RCP8.5 assumed coal consumption per capita in 2100 which is 5 times current coal consumption. Even without any policy, this has now become extremely unlikely. RCP8.5 in IPCC 2014 assumed that solar PV would be three times more capital-intensive than coal in 2020, whereas it is now 20 % less capital intensive than coal. Hausfather and Peters (2020a) and Pielke & Ritchie (2020) argue that too often RCP8.5 is considered as the standard business as usual scenario.[8]

Since the 5th IPCC report in 2014, emissions in no-policy emission scenarios have decreased in expert elicitations.

In 2015, Pindyck (2019) conducted a questionnaire among 534 scientists who had published on climate change in the preceding 10 years. On average, these experts estimated the mean growth rate of emissions in a business-as-usual scenario over the next 50 years to be 2.3 %.[9] This corresponds to a tripling of emissions over the period 2015–2065, in line with the view that RCP8.5 was a business as usual scenario.

In 2016 and 2017, Ho et al. (2019) did 3 waves of expert elicitation among energy modellers on business as usual (BAU) emissions in 2100. They found median estimates of 54, 57 and 46 GtCO2/y in the 3 waves of elicitation for scenarios which include the effect of the Paris agreement.[10] These estimates, which are in line with RCP6.0, correspond to the view that coal consumption would still rise without climate policy and that many countries would fail to update NDC's.

More recently, in July-August of 2021, RFF did an expert elicitation, not on business as usual emissions, but on unconditional likelihoods of emissions, taking into account future policy (Rennert *et al.*, 2022). Median emissions are similar to RCP4.5 (lower in

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[6] For the same reason, our estimate is more optimistic than Moore et al., (2022, sent to Nature in July 2021). Moore et al. (2022) do not model negative emissions and have therefore no scenarios which are below 1.5°C in 2100. Their overall model estimates a 28% likelihood of remaining below 2°C in 2100.

[7] Christensen, Cullingham and Nordhaus (2018) argue that future world GDP growth is larger than previously estimated, i.e. 2.6% per year, based on expert elicitation and extrapolation of past trends. The expert elicitation in Drupp et al. (2018) reports 1.7% per year in the context of climate discounting. Both studies find very large standard deviations of 1.1% and 0.91% respectively. These means include disasters such as wars as described in Barro (2009).The IMF's World Economic Outlook (2023) reports a mid-term growth of 3.1% by 2028, which is lower than the forecasts of the preceding decades.

[8] Schwalm, Glendon and Duffy (2020a) disagree with Hausfather & Peters (2020). They argue that the IEA stated policy scenario for 2050 is in the middle in between RCP8.5 and RCP4.5. However, this is based on the assumption that land use and land use change emissions would be on the same increasing trend as 2005–2019, which is very unlikely. Hausfather & Peters (2020b) show that using the land use and land use change emissions from the relevant SSP scenario, the IEA stated policy scenarios is in line with RCP4.5. Schwalm, Glendon and Duffy (2020b) also argue that cumulative emissions until 2020 are closest to RCP8.5 emissions. This is refuted in detail by Burgess et al. (2020).

[9] The question was as follows "Under BAU (i.e., no additional steps are taken to reduce emissions), what is your best estimate of the average annual growth rate of world GHG emissions over the next 50 years?" Responses were similar for experts in North-American, European and Developing Countries (2.4%, 2.1% and 2.4% respectively).

[10] Without the effect of the Paris agreement, median estimates of the 2nd and 3rd questionnaire are 71 and 67 GtCO2 respectively.

Table 4
Likelihoods of emission scenarios under different ‘coherent beliefs’ which underpin our sensitivity analysis. Deviations from the central estimates are in blue.

	SSP1-1.9	SSP1-2.6	SSP4-3.4	SSP2-4.5	SSP4-6.0	SSP3-7.0	SSP5-8.5
Temp in 2100 (median)	1.4 °C	1.8 °C	2.25 °C	2.7 °C	3.2 °C	3.6 °C	4.4 °C
Central estimate	15 %	25 %	25 %	20 %	10 %	4 %	1 %
Optimistic	20 %	25 %	25 %	20 %	7 %	2 %	1 %
Pessimistic	10 %	25 %	25 %	20 %	12 %	6 %	2 %
Agnostic except RCP 7.0 and 8.5	18 %	18 %	18 %	18 %	18 %	6 %	2 %

2050, higher in 2100), the 95th percentile is in between RCP6.0 and RCP7.0, and the 99th percentile is slightly above RCP7.0 but far below RCP8.5. We will suggest these percentiles when we attribute likelihoods to RCP scenarios.

The likelihoods from the RFF expert elicitation are more or less in line with results in Moore et al. (2022), who create a model of the climate-social system, including the main determinants of future emission pathways. They calibrate probability distributions of socio-politico-technical feedbacks on current data where available. They establish 3 high-emission scenarios, with a joint likelihood of approximately 15 % to exceed 3 °C.[11] We will use this percentage in our central estimate. The study shows that by adding socio-politico-technical uncertainty to the model, the set of future possibilities becomes large. This is intuitive. Experts in 1950 would have done a poor job at forecasting today’s society.

The most likely driver of high emission scenario in Moore et al. (2022) is higher-than-expected marginal abatement costs, with lower technological learning by doing effects. So even without policy reversal, emissions may turn out to exceed RCP4.5, as in the NGFS ‘hot world scenarios’. This can be understood by acknowledging that, under current policy scenarios, abatement costs are relatively high. The Supplementary Information (Online Resource 1, SI 1) shows that the median abatement costs in 2050 of the scenarios between 2.4 °C and 3 °C represent 2.3 % of GDP with a median marginal abatement cost of 145$/tCO2. Costs in 2050 for the scenarios between 3 and 3.6 °C are much lower, 1.2 % of GDP and 53€/tCO2. Countries may renege on commitments when costs turn out to be larger than expected as was the case for Canada and the Kyoto protocol. More generally, high costs may lead to a disintegration of the Paris Agreement.

Literature on fossil fuel market mechanisms also stress that high-emission futures remain possible. Fossil fuel supply side dynamics may make international agreements and ambitious climate scenarios more challenging. Current reserves of oil gas and coal correspond to 2900 GtCO2, but ultimately recoverable fossil fuel resources are 4 times larger (McGlade and Ekins, 2015). In other words, there are enough fossil fuels to realize the RCP8.5 scenario. To stay below 2 °C, even in scenarios with CCS, 33 % of current oil reserves, 49 % of gas reserves and 82 % of coal reserves are unburnable (McGlade & Ekins, 2015). To stay below 1.5 °C, 58 % of oil, 56 % of fossil methane gas and 89 % of coal reserves are unextractable by 2050 compared to a 2018 reserve base (Welsby et al., 2021). The current fossil fuel prices include scarcity rents based on the anticipation that fossil fuels will become scarcer over time. Once there is a consensus that some of the existing reserves will never be exploited, producers will start a race to exploit all of their reserves before others do. This competition will dissipate rents and push prices towards their production costs, which are around 20 or 30$/tonne for known reserves. The IEA (2022) assumes indeed that in a zero emission scenario fossil fuel prices plateau in 2025 and start to decline thereafter. It will make abatement more challenging because dirty technologies will be cheaper and will also increase carbon leakage when countries have different levels of climate ambition. For fossil fuel producing countries, the loss of oil rents is likely to lead to political crisis.

There are also arguments which make very high temperatures less likely. Confronted with large damages of warming beyond 3 °C, solar radiation management may be seen as the lesser of two evils. There is also a question whether the marginal abatement costs in integrated assessment models are in line with recent bottom-up cost estimates. In the Supplementary Information (Online Resource 1, SI 2) we argue that high-end abatement opportunities applicable at large scale such as direct air capture and storage (DACCS), enhanced weathering of olivines and advanced hydrogen may be available at acceptable costs, around 100 to 200$/tCO2, much lower than the cost in integrated assessment models.

Overall, it is not likely that the modest current climate policies will be reversed. Given the current pledges, it seems more likely that we will see an increase in climate policy ambition rather than a decrease. Also, past forecasts of BAU emissions tend to have overestimated emissions, mainly due to an underestimation of the learning speed of renewables. Therefore, the scenarios RCP6.0, RCP7.0 and RCP8.5 are unlikely. However, they are possible if existing policy would be abandoned, like under the Trump administration, if abatement technologies such as CCS would be much harder to realize than anticipated or if very large international rivalry would jeopardize international collaboration.

7. Probabilities of emission scenarios

Many companies now conduct extensive climate risk analysis for internal risk management purposes as well as for publicly reporting under the auspices of the Task-force on Climate related Financial Disclosure (TCFD, 2022). New standards issued by the International Sustainability Standards Board (ISSB, 2023) have become effective on 1st January 2024 and fully incorporate the TCFD

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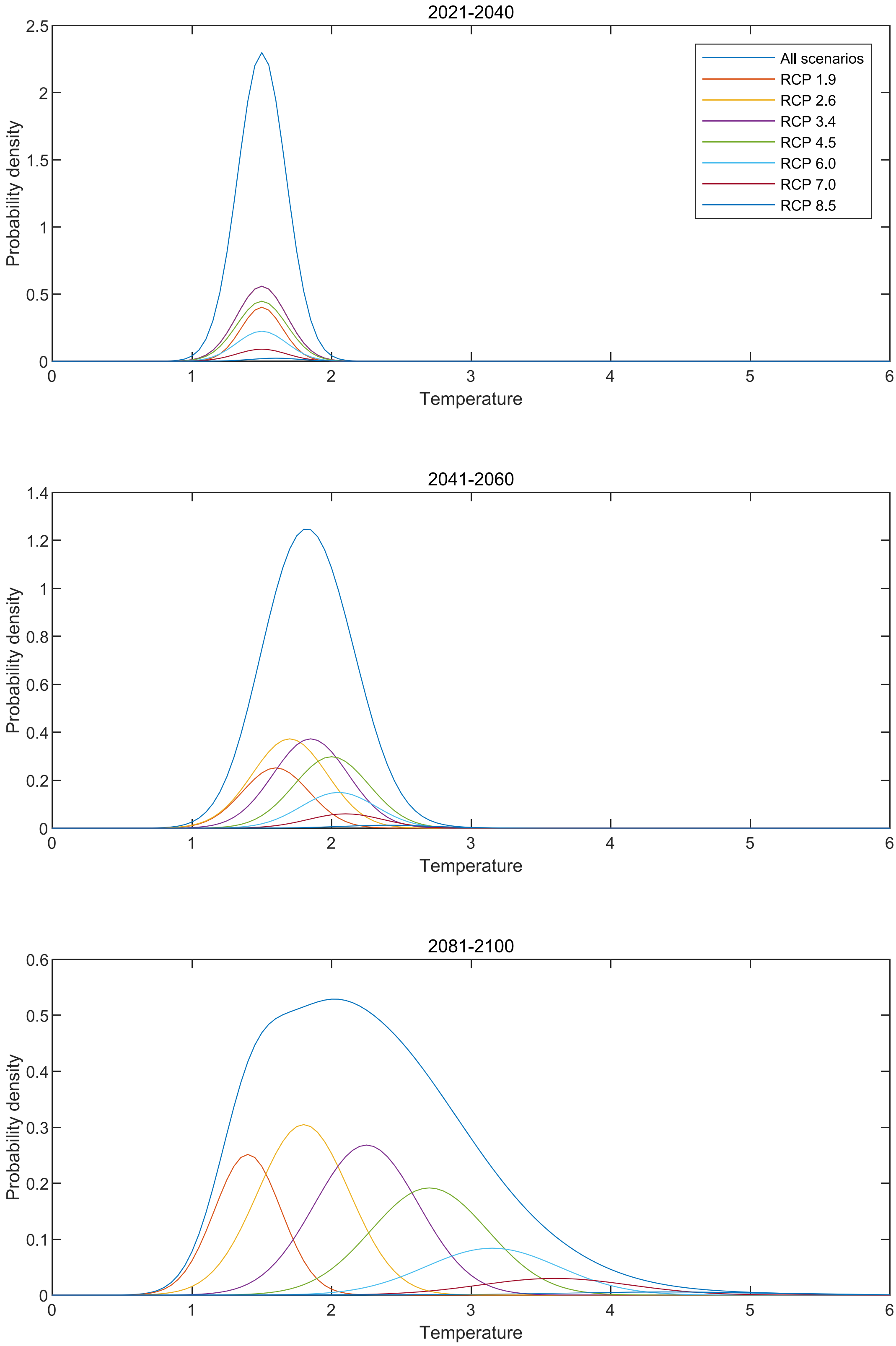
[11] The ‘Technical Challenges’ scenario has a median warming of 3°C, implying that half of these scenarios result in temperatures beyond 3°C.



(caption on next page)

Fig. 2. Probability distribution of temperatures, based on our central estimate of probabilities of emission scenarios (Table 4) and temperature uncertainties from the IPCC (Table 1). The probability densities of the individual RCP scenarios are weighted by their probability. The aggregate probability density (upper blue line) is the sum of the individual RCP lines. Online Resource 1 (SI 3 and 4) contains likelihoods for temperature bins and Value at Risk.

reporting recommendations. One of the key recommendations of the TCFD is to develop future scenarios, with at least one scenario with temperatures below 2 °C. Similarly, many countries and regions develop climate risk analysis, in which a wide set of future possibilities needs to be considered. This literature review aims to help these actors to envision the different futures they need to prepare for and to attach weights to those scenarios. These weights, although subjective, are a requirement to incorporate the output of these scenarios into decision making. This section gives guidance for this process.

In a society with heterogenous agents, alternative, subjective beliefs on the likelihoods of emission scenarios are unavoidable. Therefore, we provide an excel sheet (Online Resource 3) where governments, companies and NGO's can fill in their beliefs regarding future emission scenarios and obtain a probability distribution of temperatures, by combining uncertainty of future emissions with the uncertainty in the climate system (Table 1).

The reviewed literature indicates that RCP's 2.6, 3.4 and 4.5 are likely, because they span the possible outcomes between the current policy scenarios and announced pledges scenarios. We have argued in the preceding sections why the scenarios outside these ranges can be considered less likely.

We could have stopped our article here. However, to evaluate how sensitive temperatures are to emission scenario likelihoods outside the likely range, we will show results where we attach a 10 %, 15 % and 20 % likelihood to scenarios below and above the three central RCP's. We also provide an 'agnostic' scenario, which equally weights each RCP scenario, except for the two highest ones. The agnostic scenario has a lower probability for the middle RCP scenarios and increases the variance of the distribution. This gives rise to four illustrative 'coherent beliefs' which we will label as central, optimistic, pessimistic and agnostic. We use these 'coherent beliefs' as a way of transparently organizing the ambiguity associated with our likelihood estimates. Each policymaker, company or scientist can meaningfully argue in favour of one of them, given his informed beliefs regarding future climate policy, international coordination, technological developments as well as the impact of hitting social or physical tipping points. Alternative coherent beliefs are also possible and can be produced with our accompanying excel application. Although these likelihoods are subjective, we consider them to be non-falsifiable by the current literature. Table 4 provides an overview of the different 'coherent beliefs'.

8. Temperature probability distribution

Table 1 shows projected temperature increases and their very likely (90 %) ranges for seven scenarios from IPCC Sixth Assessment Report (Masson-Delmotte et al., 2021). These temperature ranges include many of the drivers of tipping points, such as melting of the Arctic sea ice and a shift in the thermohaline circulation, although other drivers such as methane hydrates in the deep ocean and permafrost thawing are less frequently represented in CMIP6 models. Note that many of the tipping points, although possibly irreversibly triggered in the coming decades, would lead to gradual impacts which become catastrophic only after 2100 (Dietz et al., 2021). Improved understanding of the climate, observations under the current higher greenhouse gas concentrations and inclusion of paleoclimatic observations have led to a more precise estimate of the climate sensitivity.[12]

We multiply the probabilities of the scenarios in Table 4 with the temperature probability distribution of each scenario to generate an overall probability distribution for temperature[13] in 2030, 2050 and 2090. The very likely temperature ranges are more or less symmetric around their expected value, therefore we assume a normal distribution around the mean for each emission scenario. Due to the possibility of extremely bad scenarios (RCP8.5) the aggregate probability distribution is skewed and has a fat right tail (extremely high outcomes are more likely compared to an aggregate normal distribution).

Fig. 2 shows the temperature probability for 2030, 2050 and 2090 for the central case. By the end of the century, there is almost 40 % probability of warming below 2 °C, 40 % probability of warming between 2 °C and 3 °C and 20 % probability of warming beyond 3 °C.[14]

The sensitivity analysis in Fig. 3 shows that the role of uncertainty in future emissions and uncertainty in the climate system is very different for 2030, 2050 and 2100. For 2030, the temperature distribution is almost entirely driven by uncertainty in the climate system. Different emission scenarios have very similar warming profiles (see also Fig. 2). All scenarios have 1.5 °C as best estimate.

In 2050, the emission scenario matters, but not enough to create large variation in our aggregate sensitivity analysis (Fig. 3). Warming exceeds 2 °C with a 33 % likelihood which may be 30 % to 37 % under alternative beliefs.

At the end of the century, the emission scenarios lead to extremely different temperature profiles (Fig. 2). As a result, the sensitivity analysis shows larger differences (Fig. 3). Warming exceeds 3 °C with 13 % probability in the optimistic estimate and 20.7 % in our

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[12] The climate sensitivity is defined as long term warming for a doubling of the atmospheric CO2 concentration and is estimated with a likely range (66%) to be between 2.5°C and 4°C, with a median estimate of 3°C. Informer IPCC reports the likely range was 1.5°C to 4.5°C.

[13] We report mean surface temperatures. Note also that land warms more than the oceans. The IPCC estimates that mean warming during the period 2010–2019 was 1.59°C on land and 0.88°C over sea.

[14] The likelihood of exceeding 3°C is 13%, 17% and 20% in the optimistic, central and pessimistic scenario. The likelihood of remaining below 2°C is 44%, 39% and 34%, in the optimistic, central and pessimistic scenario. The likelihood of remaining below 1,5° is 13% in the central scenario. See Table SI 4 (Online Resource 1).

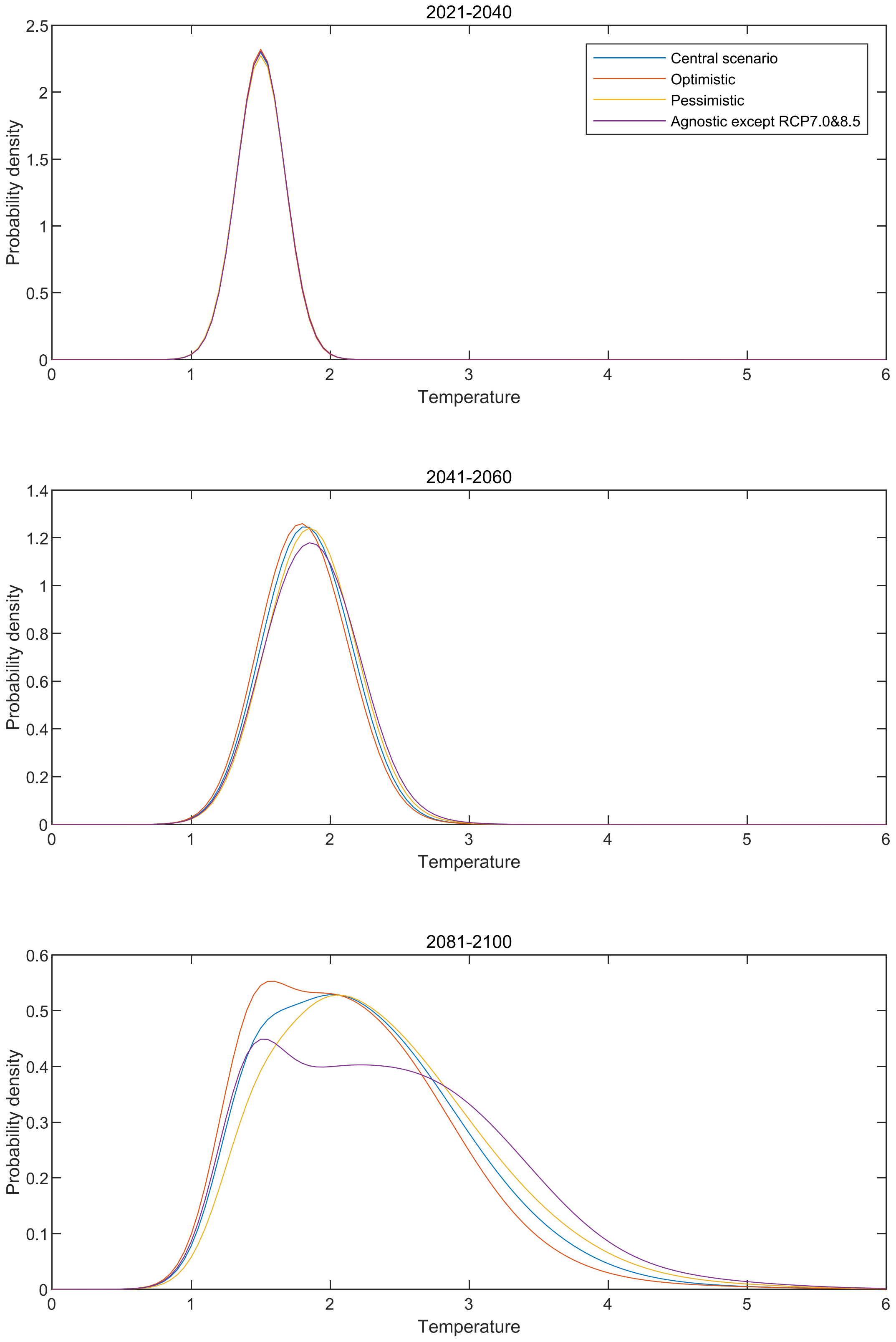

Fig. 3. Probability distribution of temperatures. Sensitivity analysis for different estimates of likelihoods of emission scenarios in Table 4.

pessimistic estimate. The temperature that is exceeded with 20 % probability is 2.7 °C in the optimistic estimate and 3.0 °C in the pessimistic estimate. Similarly, the temperature that is exceeded with 5 % probability is 3.4 °C in the optimistic estimate and 3.8 °C in the pessimistic estimate.

9. Discussion

As stated in the introduction, our likelihoods can be interpreted as Bayesian priors, which will need to be updated over time. What could increase the likelihood of low emission scenarios in the future?

The quality of institutions is crucial. 50 % of the IPCC scenarios which keep warming below 2 °C require 'unprecedented' improvements in institutional quality by 2030, a proportion which increases to 75 % by 2050 (Shukla et al., 2022; Fig TS.32). Quality of institutions is considered much more critical than the economic, technological or geophysical feasibility. This includes obviously the quality of international institutions agreements.

Future emissions will be much larger in developing countries compared to advanced economies. The share of developing countries' emissions increased from 59 % in 1990 to 76 % in 2019 (Shukla et al., 2022) and this proportion will increase further in the coming decade because emissions are expected to increase by 2 % per year this decade, whilst they were already declining over the last decade in the developed economies. Any policy or technological development in developing countries will therefore be of particular importance. Moreover, marginal abatement costs are much lower in the developing countries, especially in the poorest countries. This means that international financing mechanisms have a large potential to change future world emissions.

Abatement costs matter. Until the Paris agreement, international climate policy had been a failure overall, in stark contrast with the extremely effective Montreal protocol which ended the production of ozone-depleting gases. The fact that stopping climate change is much more costly than protecting the ozone layer helps to explain this contrast. Price instruments, such as carbon taxes and carbon markets are very effective at focussing on the cheapest abatement opportunities yielding the most 'bang for the buck'. In practice countries use a wide range of policies, some of which are also targeting low-cost opportunities. According to the 6th IPCC report (Shukla et al., 2022) the five abatement measures with the largest potential below 50$/tCO2 are solar power, wind power, nature-based solutions (avoided deforestation), industrial energy efficiency and methane abatement in oil and gas production.

Learning rates of abatement technologies have been very high historically. For technologies with a high learning rate, larger abatement costs are justified. The probabilities of emissions after 2050 are highly sensitive to the costs and feasibility of Carbon Capture and Storage (CCS), DACCS, ocean alkalinization, hydrogen and ammonia. Deployment of these technologies will be crucial, especially in developing countries.

Both the physical uncertainty of the climate system and the uncertainty regarding future emissions contribute to the long-term temperature uncertainty. In our central estimate, the emissions uncertainty is slightly more important.[15] Disentangling the main drivers behind emissions uncertainty is a fruitful area for future research and will allow us to develop temperature probabilities conditional on policy stringency, on technical change or on international cooperation. That will require further advances into socio-climate modelling ((Moore et al., 2022), Rogelj et al., 2023, Sognnaes et al., 2021).

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CRediT authorship contribution statement

Frank Venmans: Writing – original draft, Visualization, Formal analysis, Data curation, Conceptualization. **Ben Carr:** Writing – review & editing, Validation, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data is in the online materials.

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[15] For the probability distribution at the end of the century, the standard deviation in our central estimate is 0,73°C. This standard deviation is 0,41°C if we only model emissions uncertainty and 0,37°C if we only model physical climate uncertainty (for RCP3.4).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crm.2024.100605.

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