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The unconditional probability distribution of future emissions and temperatures

Frank Venmans[1] and Ben Carr[2] [3]

Abstract:

How high should we build a dyke today, knowing that it will serve for more than 50 years? This depends on the unconditional probability distribution of future temperatures. We review the literature on estimates of future emissions for current 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 policy scenarios and largely below current pledge scenarios are relatively unlikely. Based on this, we develop a transparent method to estimate unconditional probability distributions of future temperatures and temperature exceedance probabilities for use in Value at Risk stress tests in 2030, 2050 and 2100.

Keywords: Climate scenarios, temperature probabilities, current policies, announced pledges.

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. We propose a transparent weighting scheme for these conditional estimates to obtain a single, unconditional probability distribution for future temperatures. In other words, we estimate likelihoods of temperatures, taking into account all known sources of uncertainty, not only climate sensitivities, but also future policies, technological developments, international agreements, etc. This is important because for many applications, such as long-term adaptation strategies, long-term investing and insurance, a single unconditional probability distribution of future temperatures is required.

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, because even on the IPCC's most ambitious emission scenario the best estimate for warming in 2030 is 1.5°C. 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 2021).

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

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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 1990s 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 forecasting future policies, future international agreements and technological change over many decades is very difficult. There is no equivalent to the laws of physics in social sciences. 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 & King, 2020; Workman et al., 2021). The possibility of certain unknown tipping points in the climate system also contributes to deep uncertainty.

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 et al., 2020; Berger & Marinacci, 2020; Jensen & Traeger, 2022). However, even these models start from an approximating model and a ‘best guess’ for its 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. .

We organise the paper around the stylised emission scenarios from the 6th IPCC 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 (summarised in Appendix 1) and a Representative Concentration Pathway (RCP). The number of the RCP indicates the climate forcing (extra energy in Joules per m² per second) by the end of the century. The IPCC 6th assessment report uses five main reference scenarios. We will also use 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 the emission scenarios for the 7 scenarios.

We will argue that current 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 (15% likelihood for RCP1.9). Similarly, section 5 argues that scenarios exceeding current policy emissions are again relatively unlikely (15% total likelihood for RCP6.0, 7.0 and 8.5). Section 6 summarizes the likelihood of emission scenarios, Section 7 converts these emissions into temperatures and Section 8 concludes.

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 uncertainty intervals are interpolated (not reported by the IPCC).

	2021-2040		2041-2060		2081-2100	
Scenario	Best estimate (°C)	5-95% likely range (°C)	Best estimate (°C)	5-95% likely range (°C)	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

2. Current policies scenarios

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

Table 2 and Figure 1A give an overview of 12 studies estimating future emissions and temperature under a current policy scenario. Definitions of current 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 (Meinshausen et al., 2022; Sognnaes et al., 2021). Morris et al. (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 look at the higher-emission scenarios from BP and Shell, and the single forecast from ExxonMobil. None of the current 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 emissions for 2030 were reduced by 5% (UNFCCC 2022).

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 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× for solar and >100× 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 2022. 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

Figure 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 currently enacted (or announced) 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 5 other estimates of announced pledges. Emissions in 2050 are assumed to be reduced by 38% to 54%.[4] All estimates for temperatures are between 2.1°C and 2.2°C, with the exception of Meinshausen et al. (2022), who include the Indian commitment made during COP 26. Depending on conditional commitments, Meinshausen et al. (2022) estimate an emission reduction of 38% to 49% by 2050 and 2°C to 1.9°C warming in 2100. This means that, including the Indian commitment, the announced pledges scenarios have emissions slightly higher than SSP1-RCP2.6.

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, Fig2).

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.

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

Figure 1.

Emissions relative to 2021 of total greenhouse gas emissions or CO2 emissions in Current Policy scenarios (A) and Announced Pledge scenarios (B). The dotted lines are expert estimates which include future policy changes (RFF). As a benchmark, dashed lines show three RCP scenarios. Table 2 and 3 give more information on the scenarios. The online appendix contains the underlying data on absolute emissions.

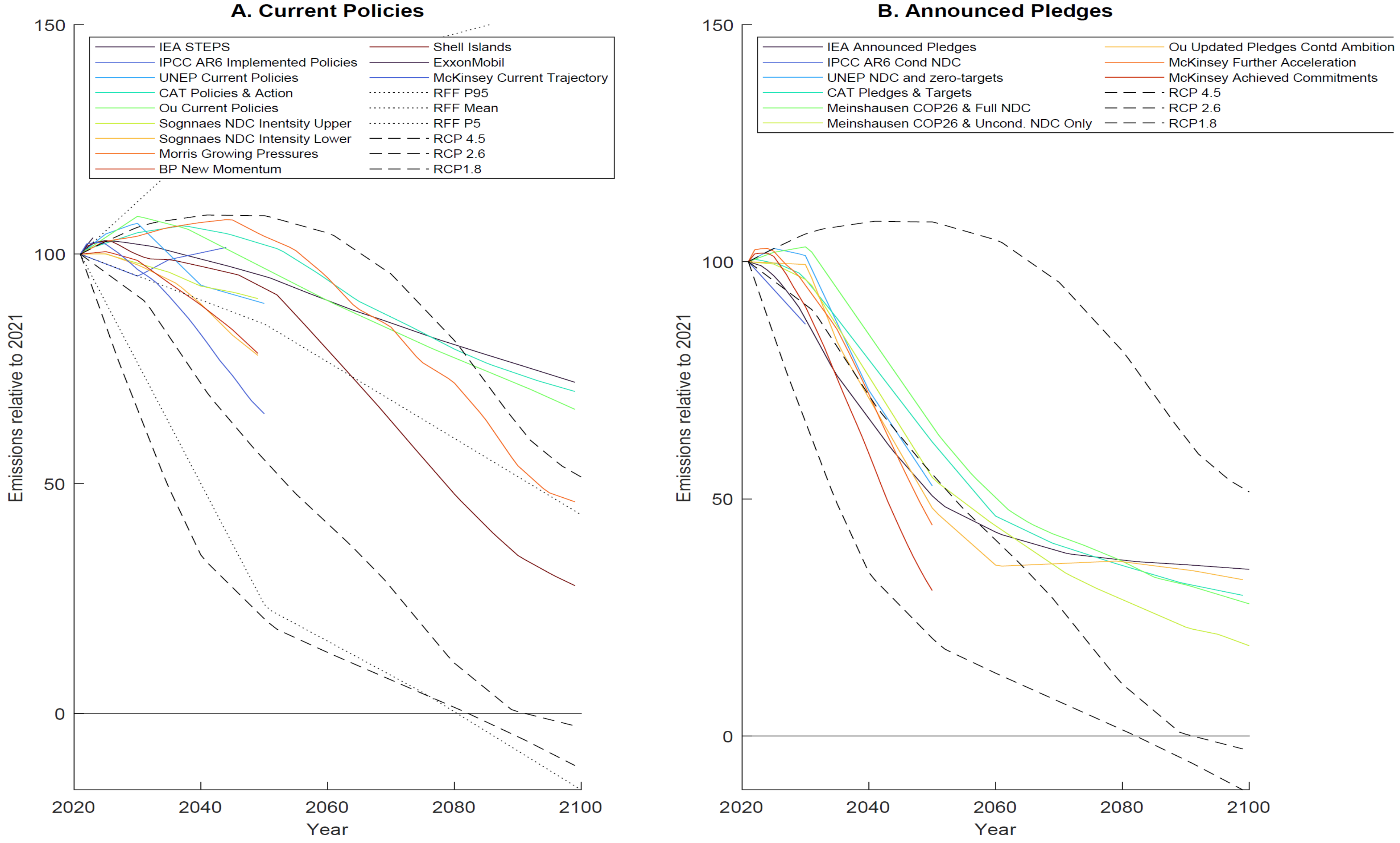

Table 2. Description of current policy scenarios. None of the scenarios include zero emission pledges, some scenarios include NDC's for 2030.

Source	Year	Name	GHG	Emissions 2019-2050	Temperature in 2100	Description
IPCC WGIII	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	2021	States 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	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	2022	Policies and actions	All	-10% to +10%	2.7°C	Real world action based on current policies.
Meinshausen et al.	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.
Sognnaes et al.	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.	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.	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	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	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.
McKinsey Global Energy Perspective	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	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 modeling and expert elicitation. Based on 10 interviews with experts, weighted by their performance on known quantities, each lasting 2h, 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.

Table 3. Description of Announced Pledges scenarios.

Source	Year	Name	GHG	Emissions 2019- 2050	Temperature in 2100	Description
IPCC WGIII	2021	NDC's conditional	All	-10% in 2030		NDC's prior to COP26 including conditional elements.
IEA Energy Outlook	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	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	2022	Pledges & Targets	All	-41%	2.1°C	Includes net-zero pledges but not those made during COP26.
Meinshausen et al.	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.	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.
BP Energy Outlook	2022	Accelerated		-75%		Middle scenario of three scenarios which "explore the range of possible outcomes".
McKinsey Global Energy Perspective	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	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.

Several changes over the last 3 years can help to explain more recent updates in climate policy ambition. Forest fires, droughts and floods have raised public awareness, leading to large protest movements (strikes for the climate with Greta Thunberg in Europe for example). Covid has increased the perception that we are more vulnerable to disasters than previously thought. Technological shifts, with Tesla's market value almost exceeding the value of all other car makers put together, has changed countries' perception of competitiveness, showing the risk of becoming a green innovation laggard. The US re-joining the Paris agreement has also increased confidence in the international negotiations.

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. Therefore it is 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. Currently proposed investments in coal will add another 97GtCO2 and investments in gas and oil will add a similar 92GtCO2. So, existing and currently planned infrastructure will emit 847GtCO2, i.e., the entire emission budget to stay below 2°C (890 GtCO2). According to the IEA's Announced Pledge Scenario, coal power plant retirements will increase from 25GW in the past decade to 49GW, 33GW and 3GW 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.

A 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 is may be quite costly. Appendix 2 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%). The marginal abatement cost, which corresponds to the carbon price if regulation is based on a price mechanism, is \$119/tCO2 (\$79-\$231/tCO2). Note that the estimates of these costs have decreased over time, because the learning speed of technologies has been underestimated in the past. Costs in the 6th IPCC assessment report are slightly smaller. However, most models do not take into account that marginal abatement costs will differ between countries and sectors, which will largely increase total costs.

We are nowhere near these implicit abatement costs. As a result, world emissions in 2019 were larger than ever (IPCC 2021), increasing by 2GtCO2 per year, which in absolute value is higher than preceding decades.[5] Although the pandemic led to the largest decrease in emissions ever, emissions in 2021 were only slightly lower than in 2019 (IEA 2021).

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 total cost of 2% to 4% of global GDP.

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[5] The growth rate of emissions decreased from 2.1%/year between 2000 and 2009 to 1.3%/year between 2010 and 2019.

4. 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?[6]

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. This is an enormous effort, representing 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 these investments are unlikely to happen.

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: "Stopping all new investment decisions in coal would cancel the construction of 200 GW and avoid 0.8 Gt of CO2 emissions in 2030. Another 150 GW of coal capacity could be closed at no cost to consumers in addition to the 480 GW retired in the Announced Policy Scenario to 2030." (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).

Also, retiring existing coal fired power plants in countries with growing energy needs is a difficult political process. 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. It requires 50 GW of coal to be retired in emerging markets and developing countries in the coming decade and another 50GW between 2030-2040. That is unlikely to happen. The average age of existing coal fired power plants is 40 and 35 years in the US and Europe respectively, and just around 12 years in India, China and Southeast Asia.

The second most important lever for cost-effective emission reductions is methane: "Reducing methane emissions is also a critical lever to close the 2030 ambition gap. Fossil fuel methane emissions are almost 2 Gt CO2-eq higher in the Announced Policy Scenario than in the Net Zero Emission scenario in 2030, largely because about 60% of current methane emissions come from countries without net zero pledges. We estimate that almost 1.7 Gt CO2-eq of this gap could be closed cost-effectively in the Net Zero Emission scenario by 2030." (IEA 2021) Again, the existence of cost-effective measures makes more ambitious scenarios more likely and show potential for better financing mechanisms. However, most of these opportunities are situated in poor countries with limited climate policy and many hurdles to investment. If cost-effective emission reductions were easy to realize they would no longer exist.

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 policy which deliberately strands industrial assets is politically very difficult. Emissions after

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[6] Under the RCP1.9 scenario, the expected warming is 1.5°C in 2030 and 1.6°C in 2050 with cooling thereafter due to large net negative emissions.

2030 are much more difficult to predict, because it will be very sensitive to policy ambition in the coming years.

The effect of other anthropogenic climate forcers 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 (IPCC AR6 WGI). Yet aerosols will decrease in the future, because they cause 4.2 million deaths per year (WHO, 2021), 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 faster than expected. 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 (damages and gains from climate change are unevenly distributed and countries have different stances on risks related to geo-engineering) (Aldy et al. 2021).

RCP1.9 is based on a massive amount of negative emissions in the second half of the century. Biomass Energy with Carbon Capture and Storage (BECCS) is the main negative emission technology in forecasts, but it is constrained by the available biomass. Direct Air Capture and Storage and mineral weathering do not require biomass, but are costly (Appendix 3).

Given the above, it is tempting to give very low likelihood to extreme scenarios such as RCP1.9. However, 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 & King, 2020; Workman et al., 2021). One has to think about how accurate economists were 80 years ago (in 1942) at predicting population, GDP, technology and political systems of today's society. With this in mind, we will show results where we attribute 10%, 15% and 20% likelihood to the scenarios that go beyond current pledges.[7]

5. 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[8] 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 (IPCC 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 overaggressive use of coal compared to the past. Coal consumption would be 5 times larger in 2100 compared to today.

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[7] This is more optimistic than the expert panel questioned by the RFF, who gave a 5% probability of exceeding the ambition of the RCP2.6 scenario. They were questioned in the summer of 2021. Since then, new NDC's, mainly by Indonesia, China and India have reduced the cumulative emissions of the pledges by 250GtCO2 and reduced likely peak warming by 0.3°C (Meinshausen 2022).

[8] Until 5 years ago, the difference between current policy scenarios and no policy scenarios was rarely made. Both were called reference, baseline or business-as-usual scenarios.

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.[9] They show that the IPCC (2014) scenarios have overestimated emissions, mainly due to an overestimation of GDP growth[10] and the assumption of an increasing trend in coal consumption. Most IPCC (2014) 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 (2020) and Pielke & Ritchie (2020) argue that too often RCP8.5 is considered as the standard business as usual scenario.[11]

Since the 5th IPCC report (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%.[12] 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.[13] 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 (2021) did an expert elicitation, not on business as usual emissions, but on unconditional likelihoods of emissions, taking into account future policy. Median emissions are similar to RCP4.5 (lower in 2050, higher in 2100), the 95th percentile is in between RCP6.0 and RCP7.0, and the 99th percentile is slightly above RCP7.0

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[9] The IEA is often taken as a reference forecaster, it has a good historical record of relative precise predictions, although it did not forecast the fast cost reduction in renewables (Fazendeiro, Simões 2021).

[10] 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.

[11] 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 (2020a) also argue that cumulative emissions until 2020 are closest to RCP8.5 emissions. This is refuted in detail by Burgess et al. 2020.

[12] 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? (You might believe that the growth rate will change over time; we want your estimate of the average growth rate over the next 50 years under BAU.)" Responses were similar for experts in North-American, European and Developing Countries (2.4%, 2.1% and 2.4% respectively).

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

but far below RCP8.5. We will suggest these percentiles when we attribute likelihoods to RCP scenarios.

We will show temperature probability distributions assigning an overall probability of 10%, 15% or 20% to scenarios beyond RCP4.5. This non-negligible likelihood is based on the following considerations.

First, it is extremely difficult to forecast population growth, GDP, technological developments and political systems. Experts in 1940 would have done a poor job at forecasting today's society. Therefore, it is important to envision a large set of future possibilities. Even without policy reversal, emissions may turn out to exceed RCP4.5.

Second, even under current policy scenarios, abatement costs are relatively high. Appendix 2 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.

Third, 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). 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 assumes 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 appendix 3 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, or if abatement technologies such as CCS would be much harder to realize than anticipated or if very large international rivalry would jeopardize international collaboration.

6. Probabilities of emission scenarios

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 chapters why the scenarios outside these ranges are unlikely.

In a society with heterogenous agents, alternative priors on the likelihoods of emission scenarios co-exist. We develop an online excel sheet where companies, citizens and governments can fill in their customized priors and obtain a probability distribution of temperatures.

We could have stopped our article here. However, to evaluate how sensitive temperatures are to these scenario likelihoods, 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 gives even weight to each RCP scenario, except for the two highest ones. Table 4 gives the overview of all scenarios. These likelihoods span the range we consider to be in line with the literature.

Table 4. Likelihoods of emission scenarios.

	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%

7. Temperature probability distribution

Table 1 shows projected temperature increases and their very likely (90%) ranges for seven scenarios from IPCC Sixth Assessment Report (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.[14]

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[14] 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.

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[15] in 2030, 2050 and 2090. The very likely ranges are more or less symmetric around the 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).

The results are reported in Table 5 and Figure 2 and follow approximately a 40-40-20 pattern: 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.

Table 5. Likelihood for temperature at the end of the century (2081-2100). Based on the probabilities of RCP's from Table 4 and temperature estimates in Table 1.

Temperature	<1°C	1-1.5°C	1.5-2°C	2-2.5°C	2.5-3°C	3-4°C	4-5°C	5-6°C
Central estimate	0.7%	13.1%	25.2%	25.3%	18.9%	14.5%	1.9%	0.2%

	<1°C	1-2°C	2-3°C	3-4°C	4-5°C	5-6°C
Central estimate	0.7%	38.4%	44.2%	14.5%	1.9%	0.2%
Optimistic	0.9%	43.2%	43.0%	11.5%	1.3%	0.2%
Pessimistic	0.5%	33.6%	45.2%	17.3%	3.0%	0.4%
Agnostic	0.8%	34.8%	38.8%	21.1%	4.0%	0.6%

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

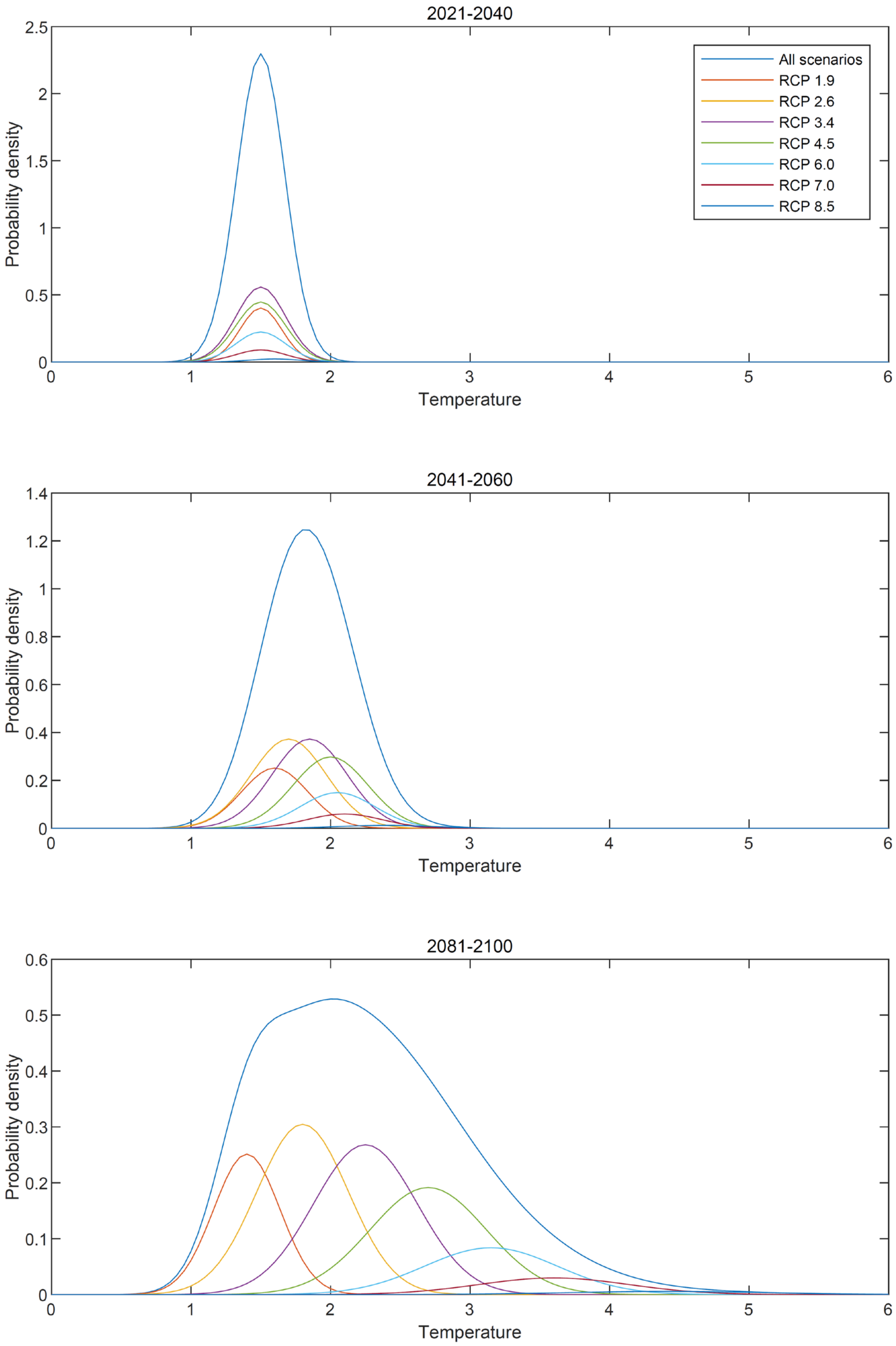

Figure 2. Probability distribution of temperatures, based on our central estimate of probabilities of emission scenarios (in Table 4) and temperature uncertainties from the IPCC (2021, Table 1). The probability densities of the individual RCP scenarios are weighted by their probability. The aggregate probability density (upper blue line) is the sum of the individual RCP lines.

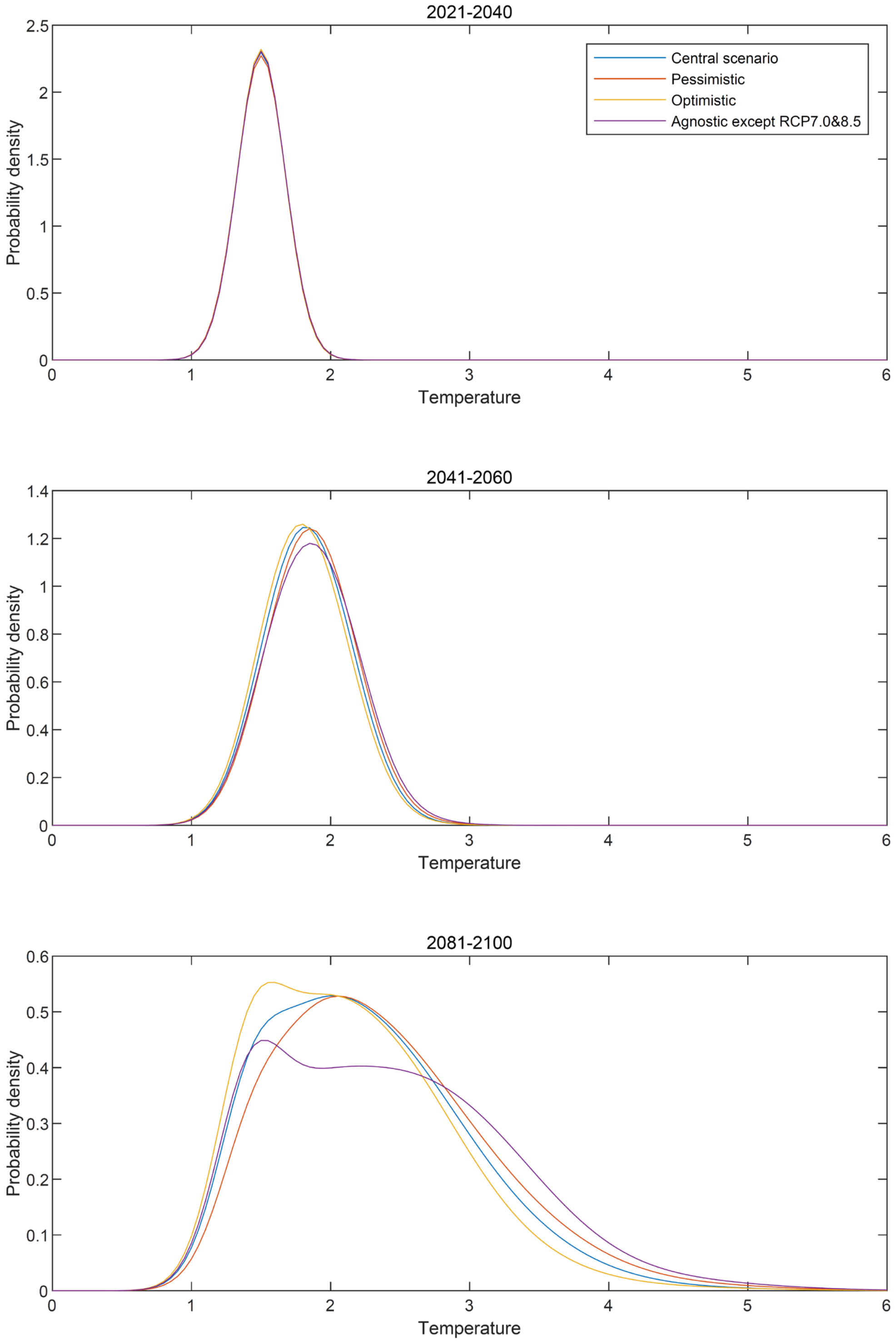

Figure 3. Probability distribution of temperatures. Sensitivity analysis for different estimates of likelihoods of emission scenarios in Table 4.

Table 6. Temperatures exceeded with different likelihood thresholds for use in Value at Risk stress tests.

Central estimate:15% likelihood of RCP6.0 and above

Period	Temperature exceeded with 20% probability	Temperature exceeded with 10% probability	Temperature exceeded with 5% probability	Temperature exceeded with 1% probability
2021-2040	1.6	1.7	1.8	1.9
2041-2060	2.1	2.2	2.3	2.6
2081-2100	2.8	3.2	3.6	4.3

Optimistic estimate: 10% likelihood of RCP 6.0 and above

Period	Temperature exceeded with 20% probability	Temperature exceeded with 10% probability	Temperature exceeded with 5% probability	Temperature exceeded with 1% probability
2021-2040	1.6	1.7	1.8	1.9
2041-2060	2.1	2.2	2.3	2.5
2081-2100	2.7	3.1	3.4	4.2

Pessimistic estimate: 20% likelihood of RCP 6.0 and above

Period	Temperature exceeded with 20% probability	Temperature exceeded with 10% probability	Temperature exceeded with 5% probability	Temperature exceeded with 1% probability
2021-2040	1.6	1.7	1.8	1.9
2041-2060	2.1	2.3	2.4	2.6
2081-2100	3.0	3.4	3.8	4.6

Agnostic estimate: 26% likelihood of RCP 6.0 and above

Period	Temperature exceeded with 20% probability	Temperature exceeded with 10% probability	Temperature exceeded with 5% probability	Temperature exceeded with 1% probability
2021-2040	1.6	1.7	1.8	1.9
2041-2060	2.1	2.3	2.4	2.7
2081-2100	3.1	3.5	3.9	4.8

8. Conclusion

The sensitivity analysis in the preceding chapter is very different for 2030, 2050 and 2100.

For 2030 (2021-2040), the temperature distribution is almost entirely driven by uncertainty in the climate system. Different emission scenarios have very similar warming profiles (Figure 2). All scenarios have 1.5°C as best estimate.

In 2050 (2041-2060), the emission scenario matters, but not enough to create large variation in our aggregate sensitivity analysis (Figure 3). Warming exceeds 2°C with a 33% likelihood which may be 30% to 37% under alternative beliefs.

In 2100 (2081-2100), the emission scenarios lead to extremely different temperature profiles (Figure 2). As a result, the sensitivity analysis shows larger differences (Figure 3). Warming exceeds 3°C with 13% probability in the optimistic estimate and 20.7% in our 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. However, this is very different from the common practice of ten years ago which was to consider RCP8.5 as the business as usual scenario (Hausfather & Peters 2020).

As stated in the introduction, our likelihoods can be interpreted as Bayesian priors, a best guess, 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, 2022, Fig TS.32). Quality of institutions is considered much more critical than the economic, technological or geophysical feasibility.

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 (IPCC 2021) and this proportion will increase further in the coming decade because emissions are expected to increase by 2% per year during the 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, climate policy had been an international 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. Table 7 shows the technologies with the highest abatement potential below a cost of 50$/tCO2 by 2030 (Shukla, 2022).

Learning rates of abatement technologies have been very high historically. Abatement in developed economies is crucial because it will allow high-end abatement technologies to become cheaper. For technologies with a high learning rate larger abatement costs are justified. The probabilities of emissions after 2050 are especially sensitive to the costs and feasibility of Carbon Capture and Storage (CCS), DACCS, ocean alkanisation, hydrogen and ammonia.

Table 7. Emission mitigation options with the largest abatement potential below a cost of 50$/tCO2eq in 2030. As a reference, global emissions in 2019 were 59GtCO2eq (IPCC, Shukla 2022)

Abatement measure	Potential abatement (GtCO2eq/year)
Solar energy	3.3
Wind energy	3.2
Reduce conversion of natural ecosystems (deforestation)	2.2
Energy efficiency in industry	1.2
Reduce CH4 emissions from oil and gas	1.1
Reduce emissions from fluorinate gases	0.9
Efficient lighting, appliances and equipment in buildings	0.8

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Statements and declarations

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10. Appendices

Appendix 1 Narratives for each Shared Socioeconomic Pathway (Riahi et al. 2017).

SSP1 - Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation) The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, educational and health investments accelerate the demographic transition, and the emphasis on economic growth shifts toward a broader emphasis on human well-being. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity.

SSP2 - Middle of the Road (Medium challenges to mitigation and adaptation) The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work toward but make slow progress in achieving sustainable development goals. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves only slowly and challenges to reducing vulnerability to societal and environmental changes remain.

SSP3 - Regional Rivalry – A Rocky Road (High challenges to mitigation and adaptation) A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. Policies shift over time to become increasingly oriented toward national and regional security issues. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development. Investments in education and technological development decline. Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time. Population growth is low in industrialized and high in developing countries. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions.

SSP4 - Inequality – A Road Divided (Low challenges to mitigation, high challenges to adaptation) Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries. Over time, a gap widens between an internationally-connected society that contributes to knowledge- and capital-intensive sectors of the global economy, and a fragmented collection of lower-income, poorly educated societies that work in a labor intensive, low-tech economy. Social cohesion degrades and conflict and unrest become increasingly common. Technology development is high in the high-tech economy and sectors. The globally connected energy sector diversifies, with investments in both carbon-intensive fuels like coal and unconventional oil, but also low-carbon energy sources. Environmental policies focus on local issues around middle and high income areas.

SSP5 - Fossil-fueled Development – Taking the Highway (High challenges to mitigation, low challenges to adaptation) This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated. There are also strong investments in health, education, and institutions to enhance human and social capital. At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world. All these factors lead to rapid growth of the global economy, while global population peaks and declines in the 21st century. Local environmental problems like air pollution are successfully managed. There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary.

Appendix 2. Abatement costs in IPCC and NGFS scenarios

Table A2. Total abatement costs as a % of GDP and marginal abatement costs in $2015 per tonne of CO2 for different groups of abatement scenarios. All scenarios in the IPCC special report on 1.5°C (IPCC 2018) and Network for Greening the Financial System database (NGFS 2021). P25 is 25th percentile, p75 is 75th percentile.

			2030					
Cumulative Emissions	**Temperature in 2100**	**#scenarios**	Total cost (%GDP)			Marginal cost or carbon price ($/tCO2)		
			p25	median	p75	p25	median	p75
<1350	<2°C	67	2.0%	3.1%	3.9%	79	119	231
1350-2000	2-2.4°C	53	1.0%	2.2%	3.4%	45	73	150
2000-3000	2.4-30°C	41	0.6%	1.2%	1.4%	36	54	71
3000-4000	3-3.6°C	21	0.0%	0.5%	0.8%	9	25	30

			2050					
			Total cost (%GDP)			Marginal cost or carbon price ($/tCO2)		
			p25	median	p75	p25	median	p75
<1350	<2°C	67	2.9%	4.1%	6.0%	308	427	911
1350-2000	2-2.4°C	53	1.6%	2.7%	4.3%	148	210	293
2000-3000	2.4-30°C	41	1.6%	2.3%	3.0%	99	145	177
3000-4000	3-3.6°C	21	0.3%	1.2%	1.9%	20	53	71

			2100					
			Total cost (%GDP)			Marginal cost or carbon price ($/tCO2)		
			p25	median	P75	P25	median	P75
<1350	<2°C	67	3.1%	6.2%	9.0%	1372	2085	3660
1350-2000	2-2.4°C	53	2.8%	4.2%	6.9%	763	1101	1959
2000-3000	2.4-30°C	41	1.7%	2.9%	5.8%	434	590	1448
3000-4000	3-3.6°C	21	0.9%	1.6%	3.6%	155	234	452

Table A2 shows that the scenarios that stay below 2°C are costly. The median cost in 2030 for scenarios below 2°C is 3.1% of world GDP in 2030 and a quarter of the scenarios have costs beyond 3.9% of GDP. In 2050, the median costs is 4.1% and a quarter of scenarios have costs exceeding 6.0% of GDP. The marginal abatement costs is the cost of the most expensive technology at a given moment in time (for example hydrogen or CCS). It also corresponds to the necessary carbon price if abatement is obtained with a carbon tax. The median marginal abatement costs is $119/tCO2 in 2030 and $427/tCO2 in 2050. In our note on optimal climate policy (see attachment) we argue that some of these costs are relatively high. But even if 75% of the models overestimate the cost (and merely 25% of the models underestimate the cost), staying below 2°C requires a carbon price of $79/tCO2 in 2030 and $308/tCO2 in 2050 (Percentile 25 in Table 2). Even for scenarios that lead to warming between 2.5°C and 3°C at the end of the century, abatement costs are relatively high. In 2030 the median model shows a total cost of 1.2% of GDP and a marginal abatement cost of $54/tCO2.

These large costs lead to scepticism about the realism of countries' targets among a subset of economists (Nordhaus 2021, Barrett & Tannenberg 2022). They argue that the current zero emission commitments are likely to be abandoned when countries discover how difficult their targets are. They argue that the current zero emission scenarios will not be respected unless there is an international punishment mechanism where a club of committed countries adds a general trade tariff (on all goods, not only on carbon intensive goods) of 1 or 2% for countries that do not apply a strict climate policy. These scholars use game theory where countries are self-regarding agents without altruism for citizens in other countries nor complex election or power dynamics. The retreat of Canada from the Kyoto protocol when it turned out to be more difficult than anticipated is an example of a country that abandoned its international climate commitment without any difficulty.

Other prominent economists, argue that countries have a complex set of motives, that not delivering on promises is risky for politicians, that countries care for their international reputations and that there is a race for becoming market leader in green technologies (Stern 2021) They consider the approach of the Paris agreement, with self-announced targets without clear punishment mechanism to be effective.

Appendix 3 Marginal abatement costs of DAC, BECCS or Hydrogen.

This appendix summarizes bottom-up cost estimates of high-end abatement technologies, because they which tend to be lower than top-down costs in appendix 2. The marginal abatement technologies in the neighborhood of net zero emissions are likely to be in one of the following 3 families:

- Direct Air Capture with Carbon Capture and Storage (DACCS)
- Mineral weathering (silicate minerals can absorb CO2 and form carbonates)
- Green hydrogen fuel cells made with renewable energy (possibly applied in difficult circumstances such as airplanes).

Direct Air Capture is likely to be the most costly technology but also the most appropriate to scale up. It could therefore be the marginal abatement costs at peak temperature. Biomass energy with carbon capture and storage (BECCS), is likely to be more important in magnitude than DACCS, but since it is cheaper and limited by the availability of biomass, it is unlikely to be the marginal (most expensive) technology.

Shayegh, Bosetti and Tavoni (2021) report median cost estimates of 20 experts on DACCS of 214$/tCO2 in 2050 in a world that remains below 2°C. National Academy of Science net removal cost estimates for liquid solvent DAC are 156 $/tCO2 for a system with high-efficient solar energy and 506 $/tCO2 for a low-efficient system with wind energy. On top of the cost of capturing the CO2 from the air, there is the cost of geological storage, which is likely to be lower than 50$/tCO2. The UK Climate Change Committee (2020) estimates that in 2050, the cost of direct Air Capture in 2050, including storage is £180/tCO2. BECCS energy from waste is estimated at £160/tCO2 and BECCS in the power sector at £100/tCO2. A related technology is to decalcinate magnesium carbonate (MgCO3->MgO+CO2), apply CCS to the concentrated CO2 outflow, spread out the MgO over land where it reabsorbs CO2 for a year, recollect the MgCO3 and repeat the cycle. This would cost between $46-$159/tCO2 (McQueen et al. 2021).

Barriers to DACCS are not only technological barriers there are also societal barriers, because citizens my protest against large CCS programs.

Mineral weathering corresponds to mining and finely grinding silicate minerals which absorb CO2 when spread out in agricultural soils or in the ocean.[16] The process increases soil fertility and reduces ocean acidification. Beerling et al. (2020) calculate that 2GtCO2/year could be absorbed on agricultural land at a cost between $80 and $180/tCO2. 2GtCO2/year is a considerable amount, but only 5% of current CO2 emissions. The physical limitation is therefore the amount of agricultural land to absorb the minerals. Also, the carbon ends up in the ocean in the form of $HCO3^-$. Although this reduces acidification, it may have other yet unknown consequences at large scale.

If negative emissions are too limited to be the marginal (most expensive) cost, we can look at the most expensive abatement technologies. Hydrogen is extremely abundant as a resource, but it is costly to produce, costly to store and costly to use (explosive). The cost of hydrogen (the full chain of generating renewable energy, hydrolysis of water, storage and use in fuel cell batteries) is a good candidate for a backstop technology from the abatement side. Cost estimates do not exceed $500/tCO2 in 2050 though. The UK Climate Change Committee (2020) estimates that the use of hydrogen in the Manufacturing and Construction in 2050

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[16] The chemical reaction is $Mg_2SiO_4 + 4CO_2 + 4H_20 \rightarrow 2Mg^{2+} + H_4Si0_4 + 4HCO_3^-$ where magnesium can be also be iron or calcium. The reaction is endotherm (does not require heat) and happens naturally on a decadal scale if the rock is pulverized. Another option is to pulverize carbonates, a common current practice to combat soil acidification from farming $CaCO_3 + CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO3^-$.

would be £118/tCO2, but some applications with hydrogen or hydrogen related fuels are more expensive: Low carbon fuels in shipping £206/tCO2, low carbon heat in existing homes £220. The most expensive marginal abatement cost in the CCC report is Fabric efficiency in existing homes (£381/tCO2).

Therefore, a carbon price of $933 in 2050 in appendix 2 seems high, not in line with recent insights in the learning rate of backstop abatement technologies.

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Appendix 4 Numerical likelihoods

Central estimate

Period	<1°C	1-2°C	2-3°C	3-4°C	4-5°C	5-6°C
2021-2040	0.1%	99.5%	0.3%	0.0%	0.0%	0.0%
2041-2060	0.2%	66.7%	33.1%	0.0%	0.0%	0.0%
2081-2100	0.7%	38.4%	44.2%	14.5%	1.9%	0.2%

Optimistic estimate

Period	<1°C	1-2°C	2-3°C	3-4°C	4-5°C	5-6°C
2021-2040	0.1%	99.5%	0.3%	0.0%	0.0%	0.0%
2041-2060	0.2%	69.6%	30.2%	0.0%	0.0%	0.0%
2081-2100	0.9%	43.2%	43.0%	11.5%	1.3%	0.2%

Pessimistic estimate

Period	<1°C	1-2°C	2-3°C	3-4°C	4-5°C	5-6°C
2021-2040	0.1%	99.5%	0.4%	0.0%	0.0%	0.0%
2041-2060	0.1%	63.5%	36.2%	0.1%	0.0%	0.0%
2081-2100	0.5%	33.6%	45.2%	17.3%	3.0%	0.4%

Agnostic estimate

Period	<1°C	1-2°C	2-3°C	3-4°C	4-5°C	5-6°C
2021-2040	0.1%	99.5%	0.4%	0.0%	0.0%	0.0%
2041-2060	0.1%	62.2%	37.5%	0.1%	0.0%	0.0%
2081-2100	0.8%	34.8%	38.8%	21.1%	4.0%	0.6%

Central estimate:15% likelihood of RCP6 and beyond

Period	Temperature exceeded with 20% probability	Temperature exceeded with 10% probability	Temperature exceeded with 5% probability	Temperature exceeded with 1% probability
2021-2040	1.6	1.7	1.8	1.9
2041-2060	2.1	2.2	2.3	2.6

2081-2100	2.8	3.2	3.6	4.3

Optimistic estimate: 10% likelihood of RCP6 and beyond

Period	Temperature exceeded with 20% probability	Temperature exceeded with 10% probability	Temperature exceeded with 5% probability	Temperature exceeded with 1% probability
2021-2040	1.6	1.7	1.8	1.9
2041-2060	2.1	2.2	2.3	2.5
2081-2100	2.7	3.1	3.4	4.2

Pessimistic estimate: 20% likelihood of RCP6 and beyond

Period	Temperature exceeded with 20% probability	Temperature exceeded with 10% probability	Temperature exceeded with 5% probability	Temperature exceeded with 1% probability
2021-2040	1.6	1.7	1.8	1.9
2041-2060	2.1	2.3	2.4	2.6
2081-2100	3.0	3.4	3.8	4.6

Agnostic estimate: 26% likelihood of RCP6 and beyond

Period	Temperature exceeded with 20% probability	Temperature exceeded with 10% probability	Temperature exceeded with 5% probability	Temperature exceeded with 1% probability
2021-2040	1.6	1.7	1.8	1.9
2041-2060	2.1	2.3	2.4	2.7
2081-2100	3.1	3.5	3.9	4.8