

Adequacy and feasibility of the 1.5°C long-term global limit



By Michiel Schaeffer, Bill Hare, Marcia Rocha & Joeri Rogelj from Climate Analytics.
With contributions from Kirste Macey, Marion Vieweg and Dim Coumou from Potsdam Institute for Climate Impact Research

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About the authors: Climate Analytics is a non-profit organization which brings together interdisciplinary expertise in the scientific and policy aspects of climate change. Activities include: synthesizing and advancing scientific knowledge in the area of climate change science, policy and impacts; providing science and policy support to the Least Developed Countries and Small Island Developing States in international climate negotiations, and the tracking and analysing the effectiveness of national climate policies globally with the Climate Action Tracker.

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Executive Summary

Scientific assessments have shown that impacts are projected to worsen significantly above a global warming of 1.5, or 2°C from pre-industrial levels. Such assessments have contributed to the adoption of 2°C as a global goal during the climate talks in Copenhagen in 2009. In Cancun in 2010 Climate Convention Parties agreed to review the global goal with the perspective of strengthening this to 1.5°C. Three considerations play a role in opinions about a long-term global goal:

1. Does a long-term global goal actually help to streamline global efforts to reduce greenhouse-gas emissions and inspire local initiatives?
2. Is the level adequately low to prevent dangerous interference with the climate system?
3. Is the goal feasible, given socio-economic and technical constraints?

A long-term global goal facilitates international negotiations and inspires policy worldwide.

There is significant evidence that the 2°C limit and 2020 targets consistent with this goal as assessed by IPCC in its Fourth Assessment Report have already influenced the targets and policies of countries, including the European Union, Australia, Japan, Mexico, South Korea, Brazil, Indonesia and South Africa. A few developing countries (e.g. the Maldives) have even announced goals to become carbon neutral within the next decade. Some countries have embedded these long-term goals into national legislation.

This and the fact that governments are implementing more climate and energy policies than ever before provide a strong message that the temperature limit is helpful, and, in fact, a necessary condition to enable the international community to jointly tackle the potentially catastrophic challenges of climate change. The fact that no country has yet taken sufficient action does not undermine the significance a global goal as a focal point for policy.

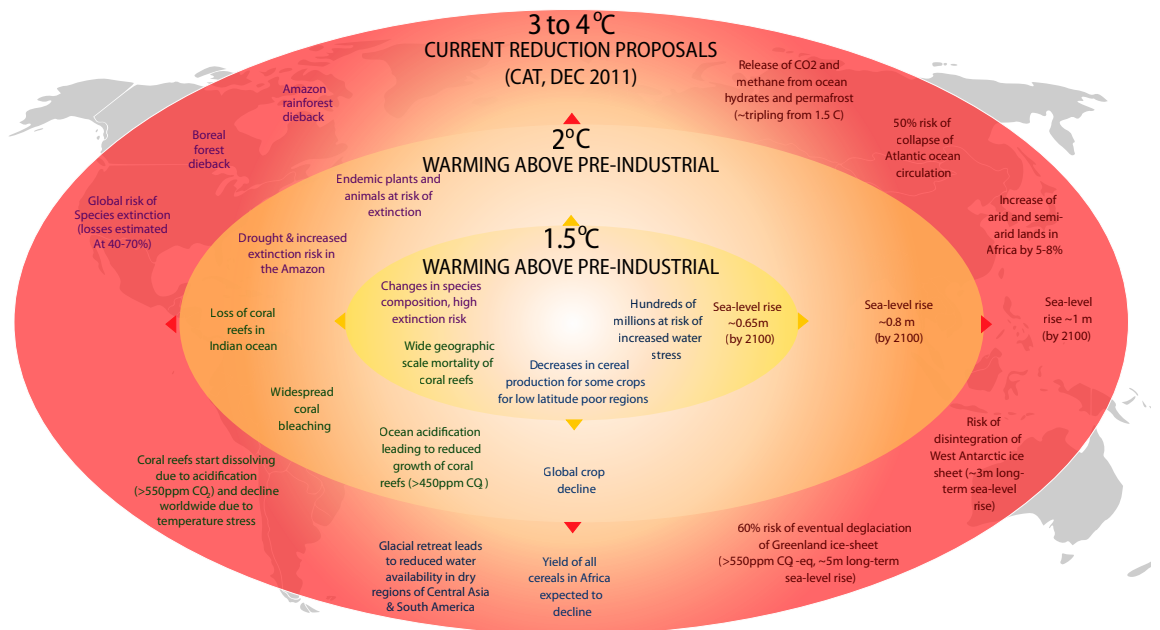
From 1.5 to 2°C warming, impacts are projected to worsen and tipping points are approached

Current warming

The past century and in particular last few decades have seen signals of anthropogenic climate change emerging as diverse as rapid sea-ice thinning in the Arctic, monthly and seasonal temperature extremes, extreme droughts in the Mediterranean, decline of coral reefs and negatively effected agricultural yields.

1.5°C above preindustrial

A 1.5°C rise by 2100 would prevent some of the worst impacts, but still poses serious challenges worldwide, especially in the LDCs, SIDS and Africa, including effects due to a decline in subtropical precipitation. In general, precipitation changes will increase water stress in regions that are already drought-affected today. Recent science shows that coral reef ecosystems are likely to be extremely adversely affected by the combined effects of ocean acidification and warming, even at levels as low as 1.5°C, compounded by the effects of a global sea level rise of 75 cm projected for this level of warming between 2000 and 2100. However, with temperatures dropping well below a 1.5°C increase, sea level rise might stabilise beyond 2100 below levels 1.5 m higher than today. Sea level rise of only 45 cm would already result in a loss of 10% of land area in Bangladesh, with flood risk there increasing most rapidly between 0 and 2°C warming. Without adaptation such moderate sea level rise will increase the number of people flooded by storm surges more than five-fold, with South and Southeast Asia being especially at risk due to vulnerable low-lying and populated deltas.



Overview of some of the impacts and tipping points at warming levels of 1.5 to 4°C above pre-industrial.
Source: www.climateactiontracker.org

2°C above preindustrial

For a warming of 2°C, severe and widespread droughts would occur in the next 30–90 years over many densely populated areas, including regions like southern Europe, Australia and large parts of Africa and North and South America. Water- and heat-stress will negatively affect crop yields in regions that are already drought-prone today, putting pressure on food security.

Drought disaster frequency in major crop-sowing areas is expected to double. Sub-Saharan crop damages might exceed 7%, with a small chance of 27% damages. In general however, crop models probably underestimate yield losses for a 2°C warming by as much as 50% for some sowing dates. 10–15% of Sub-Saharan ecosystem species would be at risk of extinction and a projected decrease in precipitation over the Amazonian forests may result in substantial forest retreat. Due to ocean acidification, coral reefs would become impeded in growth at a CO₂ concentration of 450 ppm, a level reached around 2050 on a 2°C pathway. Sea level would rise to 80 cm above 2000 by 2100, only 5 cm above 1.5°C projections, thus resulting in comparable impacts. Long-term stabilisation at 2°C warming however implies a continuous sea level rise for centuries, with levels to approach 3 m by 2300. The threshold for the Greenland ice sheet to irreversibly melt in the very long term is now estimated to be 1.6°C above preindustrial, compared to the IPCC AR4 estimate of 3.1°C.

4°C above preindustrial

Current emission trends and reduction pledges put the world on a trajectory towards a temperature increase of roughly 4°C by 2100. At such levels of warming, impacts are most severe and might be beyond the limits of adaptation. The conditions of some of the most extraordinary heat waves experienced today will become the new norm and a completely new class of heat waves, with magnitudes never experienced before, will occur regularly. This will have severe but as yet un-quantified impacts on agricultural production and human health. The timing of warming is critical as the world population is expected to grow until the second half of the 21st century.

The proportion of arid and semi-arid lands in Africa is likely to increase by 5% to 8%. Globally, drought disaster-affected areas in major crop-sowing areas are predicted to increase three-fold (from 15.4% to 44.0%) in 2100. Wheat production is likely to disappear from Africa by 2080, while millet yield in Sahelian Africa is projected to decrease by 40%. In a 4°C world, climate change may become the dominant driver of ecosystem shifts, surpassing habitat destruction as the greatest threat to biodiversity. Due to ocean acidification, corals around the world are likely to start dissolving above 550 ppm CO₂, a level reached by 2050 on a 4°C pathway. The Amazonian forest area is expected to contract to 25% of its original size and up to 30% of other tropical rainforests, in central Sumatra, Sulawesi, India and the Philippines, are threatened by forest retreat. In Africa, 25%–42% of plant species could lose all suitable range by 2085. Substantial loss of tropical forest would release large amounts of carbon dioxide into the atmosphere, which would accelerate climate change further. Sea level rise would exceed 1 m by 2100, while post-2100 sea level is hard to project, due to large knowledge gaps in understanding of the response of the ice caps to such strong warming. The potential impact of 1 m sea level rise or more would be severe, with the real risk of the forced displacement of up to 187 million people over the century (up to 2.4% of global population). East Asia, Southeast Asia and South Asia are most affected with an expected 53–125 million people displaced. The Small Island

States, Africa and parts of Asia are the most likely to see coastal abandonment as the likelihood of successful protection measures is lowest here. The frequency of the most damaging (category 4 and 5) Atlantic tropical cyclones is projected to nearly double by the end of the 21st century.

Climate change has the potential to catalyse rapid shifts in dynamic, out-of-equilibrium ecosystems, such as sudden forest loss or regional loss of agricultural productivity due to desertification. The ramifications of these shifts would be far-reaching, ranging from extensive loss of biodiversity and diminished land cover, through to loss of ecosystem services. 4°C warming by 2100 would likely result in global temperatures stabilising at 6°C above pre-industrial level over the next few centuries. No geological-historic analogue exists for the rapid warming projected under unmitigated climate change and it is fair to say that this will lead at least to widespread extinctions in ecosystems that are shown to have happened 55 million years ago during the Palaeocene-Eocene thermal maximum, which reached such a level of warming at a slower pace.

Warming can be limited to 1.5°C and below

Geophysically, warming can be limited to below 1.5°C

Hypothetically, if all emissions were to be eliminated immediately, delays in the climate system and abrupt changes in atmospheric radiative forcing would let warming continue to rise to a best-guess level of 1.2°C above pre-industrial, before embarking on a gradual decline. In the very long term, a warming limit of 1.5°C requires total greenhouse-gas concentrations plus the effects of aerosols to be below a level of 400 ppm CO₂eq. Since an immediate stop to all global emissions is obviously impossible, any mitigation pathway aiming at 1.5°C and below necessarily involves a peak-and-drop concentration profile.

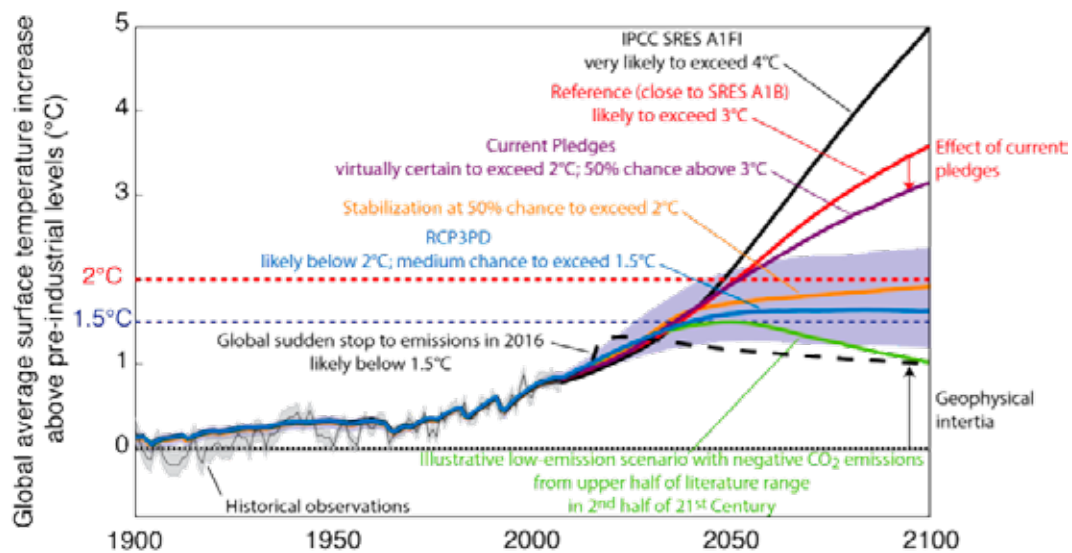
Socio-economic options for warming below 1.5°C are emerging from the scientific literature

Energy-economic models are able to achieve the required low emission levels, also without expansion of nuclear energy, but this crucially depends on:

- Early and globally concerted mitigation, emission reductions implemented from 2013 onwards and global emission peak by 2020.
- Rapid up-scaling and feasibility of large-scale bio-energy, and availability of forest sinks.
- High rates of energy efficiency improvements.
- Availability of carbon capture and storage technologies (CCS).

Large-scale deployment of biomass with CCS seems necessary for a return to below 1.5°C

Until the 2030s, long-term 1.5 and 2°C emission scenarios overlap, but a 1.5°C scenario requires deeper reductions in the rest of the 21st century. Constrained by actual emissions until 2010 and the limited energy-economic reduction potential until the 2020s, 1.5°C scenarios necessarily require net-negative CO₂ emissions in the second half of the 21st century. The later the emissions peak, the more CO₂ needs to be removed from the atmosphere starting around the 2050s. Due to slowly responding carbon pools in the Earth system, a large part of emitted CO₂ stays in the atmosphere for centuries, which is why emissions need to be reduced to near zero to stabilise concentrations. However, this also means that concentrations decrease only slowly, unless CO₂ is taken out of the atmosphere by human interventions. As biomass takes up carbon from the atmosphere through photosynthesis, capturing the CO₂ from biomass energy systems and storing it underground, it in effect produces useful forms of energy for society (electricity) while taking CO₂ out of the atmosphere – a negative emission. CO₂ removal also helps to limit acidification of the oceans.



So-called “Short-Lived Climate Forcers” do not help in the long term, but might slow near-term warming

Non-CO₂ measures must never be interpreted as a means for “buying time” to allow delayed reductions in CO₂. The probability of exceeding a 2°C warming in the 21st century more than doubles from 20% to 50%, if CO₂ reductions were delayed by just 10 years, with compensation in the near term by SLCF reductions. Given the slow removal of CO₂ from the atmosphere, this effect is set to linger for centuries. Also, after a delay in CO₂ reductions, energy-related CO₂ reduction rates need to be almost double those in a “least-cost” low-emission pathway with early CO₂ measures. Without these higher reduction rates to “catch up”, the CO₂ concentration and warming by

2100 will be even higher. From a multi-decadal perspective, delay scenarios have been shown to be riskier, with required faster CO₂ reductions after a 10-year delay too expensive and/or technically infeasible. The IEA's "World Energy Outlook 2011" states that "Delaying action is a false economy: for every \$1 of investment avoided in the power sector before 2020 an additional \$4.3 would need to be spent after 2020 to compensate for the increased emissions."

Internationally pledged emission reductions are inadequate, but options remain to close the "Gap"

2020 emission pledges are inadequate

1.5 and 2°C pathways overlap until the 2030s. For 2020 an "Emissions Gap" is estimated between, on the one hand, the global emissions level implied by current emission reduction pledges by countries and, on the other hand, the lower 2020 global emission level required to put the world on a feasible long-term emission pathway to hold warming below 1.5 and 2°C. The Emissions Gap was estimated as 6–11 GtCO₂e. Avoiding double-counting of CDM credits is required to prevent the gap from increasing by up to 2 GtCO₂e.

Options remain to close the Emissions Gap

Options to close the 2020 Emissions Gap are:

Internationally pledged emission reductions for 2020 are inadequate, but options remain to close the "Emissions Gap":

- 1) Increase the global share of renewables from an estimated 10% at present to 15% by 2020. This will help to close the Gap by 4 GtCO₂.
 - Increase further to a 20% share to close the Gap completely.
- 2) Intensify energy efficiency improvements, which would have a major impact on global energy and climate trends and would postpone a lock-in in emissions from 2017 to 2022.
- 3) Reduce subsidies for fossil fuels to decrease global emissions by 2 GtCO₂ by 2020
 - Eliminating subsidies reduces fossil-fuel demand and emissions.
 - Fossil-fuel consumption subsidies worldwide amount to \$409 billion in 2010 and may grow to \$660 billion in 2020.
 - Global renewable-energy subsidies were only \$66 billion in 2010
- 4) In the international negotiations context:
 - Implementing the more ambitious "conditional" pledges. This would reduce the gap by 2 GtCO₂e.
 - Minimising the use of lenient Land Use, Land Use Change and Forestry (LULUCF) credits and surplus emission credits. This would reduce the gap by around 3 GtCO₂e.

- Minimising the use of the surplus Assigned Amounts from the 2008–2012 Kyoto period. This would reduce the gap by 1.8 GtCO₂e.
- Avoiding the double-counting of offsets and improving the additionality of CDM projects. This would reduce the gap by up to 1.5 GtCO₂e.
- Reducing emissions from international shipping and aviation.

The required deep reductions by 2050 can only be achieved by both developed and developing countries

Global emissions must be reduced to at least 50% and probably, for a less risky pathway, to 80% below 1990 by 2050 for a 1.5°C limit in the long term. Although 2020 levels are important, mid-century levels are critical to achieving 1.5 or 2°C. For the two extreme ends of the 50–80% global reduction range, developed-country emissions need to be reduced to 85–95% below 1990, assuming developed (Annex I) and developing (non-Annex I) countries reach equal per-capita emissions by 2050, as a very simple measure of equity. Obviously, this indicator does not account for historical responsibility and other more sophisticated considerations of equity, which would in some cases imply negative emission allowances for developed countries. Some such more sophisticated considerations would also require some developing countries (like currently ‘Newly Industrialised Countries’ and ‘Rapidly Industrialising Countries’) to take on large reductions below 1990 by 2050, while for example Least Developed Countries would be exempt.

Published scenarios for EU “energy road map” go a long way, but fall short

The European Commission’s energy road map 2050 is the document that details scenarios to achieve the EU’s commitment to reducing greenhouse gas emissions to 80–95% below 1990 levels by 2050. However, as the accompanying documents specify, the actual scenarios described achieve a reduction of only 80% by 2050. As noted above, developed-countries as a group need to reduce to 85–95% below 1990 by 2050, so that the EU’s commitment is roughly consistent with a 1.5°C target, but the reductions achieved by the scenarios in the energy road map fall short.

1. Introduction

Over the past years, scientific assessments have shown that impacts are projected to worsen significantly above a global warming of 1.5, or 2°C from pre-industrial levels. Such assessments have prompted the EU to spearhead 2°C as a global goal, or limit, at the international climate negotiations and contributed to the adoption of 2°C as a global goal during the climate talks in Copenhagen in 2009. Although 2°C as a limit is not perceived universally as an uncontroversial and constructive goal, on the other hand a large group of countries proposes a lower limit of 1.5°C (See Appendix 1). Three considerations play a role in opinions about a long-term global goal:

- 1) Does a long-term global goal actually help to streamline global efforts to reduce greenhouse-gas emissions and inspire local initiatives?
- 2) Is the level adequately low to prevent dangerous interference with the climate system?
- 3) Is the goal feasible, given socio-economic and technical constraints?

We recently wrote a brief discussion on the first question in the lead-up to the 2012 UNFCCC climate talks in Doha, Qatar. The following is a reproduction of that discussion¹:

“The setting of the 2°C goal, and the corresponding call by the most vulnerable countries for the global goal to be lower, 1.5°C, reflects a common approach to resolving a wide range of ‘public good’ problems with similar characteristics. What is, for example, the ‘right’ level for standards on various air pollutants? What is the ‘correct’ speed limit that allows citizens to reach their destination in an acceptable time that minimises risk of accidents and air pollution? There is no exact scientific answer for any of these questions. However, resolving these issues requires standards – or focal points – to organise decisions around, to generate sufficient action by all parties.

The 2°C and 1.5°C limits have emerged as well-reasoned focal points for mitigating dangerous climate change. There is significant evidence that the 2°C limit has already influenced the targets and policies of countries:

- The European Union has set its 2020 policies and goals and its longer-term 2050 ambitions of an 80–95% reduction with a view to achieving the 2°C goal.
- Australia has related the upper end range of its pledges and its longer-term ambitions to conditions for a global CO₂eq concentrations limit of 450 ppm (about 40% chance to stay below 2°C in the long term).
- Japan set its 2020 target at 25% below 1990, i.e. within the oft-discussed 25% to 40% range compatible with the 2°C limit.
- Mexico increased its ambition in 2009 from 20% below BAU to 30% below BAU in 2020, the most ambitious end of the range compatible with 2°C discussed for developing countries.
- South Korea chose an unconditional target of 30% below BAU in 2020, similarly influenced by the range discussed for developing countries.
- Brazil, Indonesia, South Africa have pledged reductions that are even more ambitious than 30% below BAU in 2020.

Apart from these pledges for 2020, we also observe many countries that have announced long-term emission reduction goals for 2050, for example, Mexico, Australia and the EU. A few developing countries – Costa Rica and the Maldives – have even announced goals to become carbon neutral within the next decade. Some countries have embedded these long-term goals into national legislation.

Governments are implementing more climate and energy policies than ever before. All major economies have renewable energy targets, most supported with policies. Standards for electric appliances and buildings are used widely. Efficiency standards for passenger cars have recently been increased by, for example, USA and Canada. Emission trading systems are spreading globally with systems adopted in Australia, South Korea and China. Brazil succeeded in reducing its deforestation rate significantly, one of the biggest contributions to reductions globally by a single policy.

Together, these arguments provide a strong message that the temperature limit is helpful, and, in fact, a necessary condition to enable the international community to jointly tackle the potentially catastrophic challenges of climate change. The fact that no country has yet taken sufficient action does not undermine the significance of the 2°C goal as a focal point for policy.”

The rest of this report focuses on climate-science and energy-economic considerations to address questions 2 and 3 above, with special focus on the 1.5°C limit. As the next section shows, even at warming levels of 1.5 and 2°C, large overall negative impacts of climate change are projected over the coming century and beyond, so that a stabilisation at such warming levels does not necessarily avoid ‘dangerous climate change’. To frame the long-term warming limits, we note that these limits need to be linked back to concentrations and subsequently to emissions. Uncertainties in the climate system’s response to increased GHG concentrations mean that for a given emission pathway, it cannot be stated with absolute certainty whether a global-warming limit will be crossed or not. Instead, one has to base decisions on a certain probability whether a target will be reached. Figure 1 illustrates greenhouse-gas concentration levels that are associated with a range of warming levels. At a total greenhouse-gas concentration of 450 ppm CO₂eq, there is a likelihood of less than 50% that warming stays below 2°C in the long term. The concentration needs to stabilise at, or below 400 ppm CO₂eq for warming to stay below 2°C with a probability larger than 66%, i.e. at a ‘likely’ probability using IPCC uncertainty guidelines. At this concentration level, however, there is still not a higher than 50% probability of staying below 1.5°C in the long term, which requires concentrations at, or below 350 ppm CO₂eq. Section 3 will assess considerations of feasibility of holding warming below 1.5°C in the long term, which would require concentrations to be stabilised in the long term below present-day values (Figure 1).

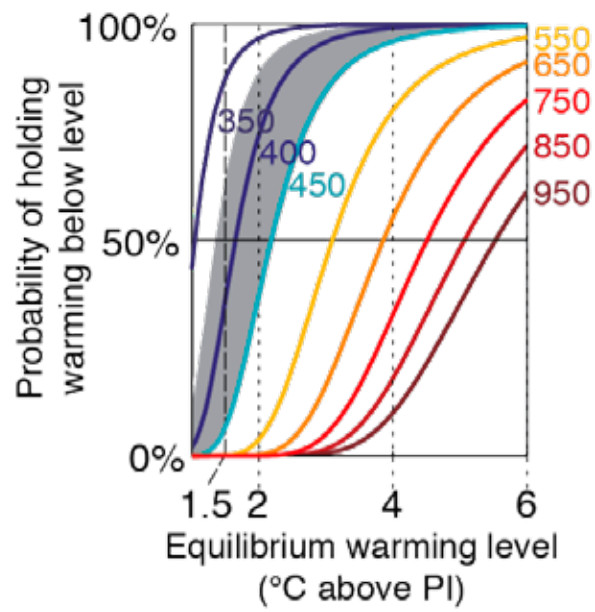


Figure 1. Probability to hold warming below temperature targets after the climate system reached equilibrium with a range of long-term fixed CO₂-equivalent concentration levels (ppm CO₂eq). The grey shaded area shows present-day CO₂-equivalent concentration without the cooling effect of aerosols (around 450 ppm) and with this cooling included (below 400 ppm). Adapted from Ref. 2.

2. Climate-change risks and impacts

Although for a single level of global warming the associated impacts are different for different regions, global-mean warming is a reasonable indicator for overall severity of climate-change impacts, generally increasing for higher levels of warming. The latest climate-model results using the new RCP^a scenarios prepared for IPCC's Fifth Assessment Report (AR5) show that the pattern of regions that are exposed to relatively large climate changes is roughly the same for global warming reaching from present-day levels to about 2.5°C above pre-industrial³. Below 2.5°C, particularly strong climate change occurs over the tropics, western China and the Arctic, compared to other regions. Above 2.5°C, however, climate change is further accelerating in particular over southern Africa, the Mediterranean and northern high latitudes, including over Siberia, Canada and US Alaska, while south-eastern Latin America, Australia, the southern Indian subcontinent and South-East Asia change at a relatively lower rate.

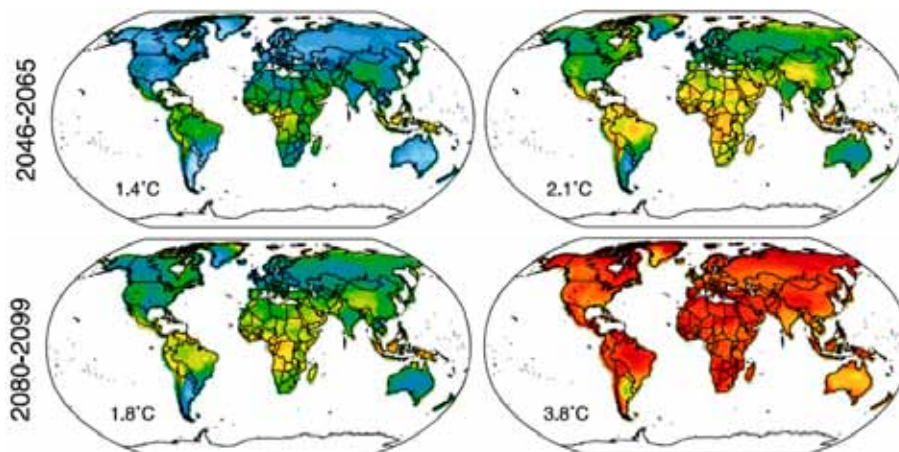


Figure 2. The relative aggregate climate change (an aggregate climate-change indicator including changes in temperatures, precipitation and extremes) between the 1986–2005 period and the 2046–2065 and 2080–2099 periods of RCP4.5 (left panels) and RCP8.5 (right panels). Source: Ref. 3.

Note that assessments of relatively high/low exposure to climate change in a certain region do not unambiguously imply that impacts are higher/lower as well, which also depends on the sensitivity of geophysical systems, ecosystems and society to changes in the physical climate system. The rest of this section provides an overview of projected impacts across warming levels, combining exposure with sensitivity. Given the wide range of sectors, systems, regions etc., this overview needs to be seen as illustrative and far from exhaustive. As such, it is useful as a brief update of some of the findings of IPCC's 2007 Fourth Assessment Report, ahead of AR5, for these illustrative sectors etc. only.

2.1 Impacts at different levels of warming^b

2.1.1 Present: 0.8°C above pre-industrial

Impact-attribution studies try to quantify the underlying forcings, of which greenhouse gas emissions is one, which could have contributed to impacts

a RCP – Representative Concentration Pathway.

b This section is adapted from Coumou, D. and M. Schaeffer (2012) "Science Update: Loss and Damage – Climate Change Today and under Future Scenarios", Climate Analytics, November 2012.

from actual extreme weather events⁴. Such end-to-end attribution science is in its infancy but qualitatively the causality between some meteorological extremes and their impact is clear. For some types of meteorological extremes there is now strong scientific evidence linking specific events or an increase in their number to the human influence on climate⁵. The frequency of extremely warm monthly and seasonal temperatures increased rapidly since the 1960s^{6,7}. This increase can largely be attributed to anthropogenic greenhouse gas forcing⁸⁻¹⁰. This implies that we can say with a high degree of confidence that recent high-impact heat waves, like the ones in Europe in 2003, Russia in 2010 and Texas in 2011, are a consequence of the limited global warming to date⁷.

Further, anthropogenic greenhouse gas and aerosol forcing are key attributable factors for the increased drying in the Eastern Mediterranean¹¹, culminating in several extremely dry years in Syria recently. As the vast majority of crops here are non-irrigated and therefore dependent on winter-time precipitation¹², the region is highly vulnerable to meteorological drought. In combination with water mismanagement, the meteorological drought in 2008 thus rapidly led to water stress, with more than 40% of the cultivated land affected, strongly reducing wheat and barley production¹². Globally, warming-induced drying has already increased the area under drought by 8%¹³, increasing water stress in vulnerable regions. Since the 1960s, sown areas for all major crops were increasingly affected by drought, with drought-affected areas for maize more than doubling from 8.51% to 18.63%¹⁴. The robustness of observed drought trends on a global scale however remains disputed (i.e. Ref. 15).

Apart from droughts, yields from annual crops like wheat and maize are negatively affected by warmer seasonal temperatures since the crop duration shortens. In addition, more frequent and intense extreme weather events, like drought and heat waves, can severely damage crop yields and thereby contribute to food price volatility¹⁶. Since the 1980s global crop production has been negatively affected by climate trends with maize and wheat production declining respectively 3.8% and 5.5% compared to a case without climate trends¹⁷. Moreover, extreme heat waves in recent years, of which some can be attributed to global warming with high confidence, caused severe damage to agricultural production in Russia (2010)¹⁸, Texas (2011)¹⁹ and U.S. (2012)²⁰. Disruptions in supply, even when relatively small, can still generate large price swings on the international market especially when stocks are limited, and hence have strong effects on vulnerable countries far removed from the location of the heat waves²¹. As an example, wheat production in Russia and Ukraine in 2010 was down by ~25% and ~20% respectively¹⁸. Since these countries are major global wheat exporters²², grain prices increased strongly on the international market. The effects were magnified when the Russian government banned grain export to protect local consumers²¹. This can lead to a panic-driven price spike due to a highly nonlinear process: Other major exporting countries limit exports in response to uncertainty in the global market, which in turn is exacerbated by these bans²¹.

Climate change to date also clearly played a role in observed ecosystem changes. Coral reefs are very sensitive to elevated sea temperatures, which cause coral bleaching²³. This sensitivity is amplified by local pollution and other human influences. Mass coral bleaching and mortality events have been observed worldwide since the early 1980s and have affected reefs at regional scales²⁴. Recent modelling studies indicate that a 1°C warming above pre-industrial levels, likely to be surpassed already in the next decade, puts about 16% of reef locations at risk²⁵. Tree die-back related to heat and drought has already been observed in boreal forest over substantial areas of North America (Allen et al., 2010).

2.1.2 1.5°C

A 1.5°C rise by 2100 would prevent some of the worst impacts, but still poses serious challenges worldwide, especially in the LDCs, SIDS and Africa. An estimated 75 to 250 million people would be at risk of increased water stress in just the next few decades²⁶. A robust response in 21st century climate simulations is a decline in subtropical precipitation and increase in high latitude precipitation^{27,28}. Thus, in general, precipitation changes will increase water stress in regions that are already drought-affected today. In Tanzania, reduced power generation from hydro-electric plants (due to water stress) alone is estimated to produce a climate-induced loss in national GDP of up to 1.7% by 2030²⁹.

Recent science shows that coral reef ecosystems are likely to be extremely adversely affected by the combined effects of ocean acidification and warming, even at levels as low as 1.5°C²⁵. Global sea level is projected to rise to 75 cm above 2000 by 2100, but can be stabilised beyond 2100 below levels 1.5 m higher than today, with temperatures dropping well below a 1.5°C increase³⁰. Sea level rise of only 45 cm would already result in a loss of 10% of land area in Bangladesh, with flood risk increasing most rapidly between 0 and 2°C warming³¹. Without adaptation such moderate sea level rise will increase the number of people flooded by storm surges more than five-fold, with South and Southeast Asia being especially at risk due to vulnerable low-lying and populated deltas³².

2.1.3 2°C

For global warming up to roughly 2.5°C³³, the hydrological response is approximately linear, with regions experiencing drier conditions under 1.5°C warming becoming even drier under warmer conditions³⁴. Severe and widespread droughts would occur in the next 30–90 years over many densely populated areas³⁵, including regions like southern Europe, Australia and large parts of Africa and North and South America. The population at risk of increased water stress would reach 350–600 million people by 2050²⁶. Still, in a 2°C warmer world, water stress will be mostly dominated by population changes rather than climate change³⁴.

Water- and heat-stress will negatively affect crop yields in regions that are already drought-prone today, putting pressure on food security. Even under low-emission scenarios, drought disaster frequency in major crop-sowing

areas is expected to double¹⁴. Sub-Saharan crop damages might exceed 7%, with a small chance of 27% damages³⁶. In general however, models tend to underestimate the damaging effects of temperature and drought extremes on crop yields^{16,37}, giving quantitative impact projections limited validity. Field experiments have shown that crops are highly sensitive to temperatures above thresholds of 30–36°C, something which is not accounted for in most crop models^{16,37}. Therefore, crop models probably underestimate yield losses for a +2°C by as much as 50% for some sowing dates¹⁶, an effect which is likely to be significantly stronger for higher levels of warming.

10–15% of Sub-Saharan ecosystem species would be at risk of extinction²⁶ and a projected decrease in precipitation over the Amazonian forests may result in substantial forest retreat here³⁸. At 2°C of warming roughly 25% of the original land extent of the humid tropical forest is at threat³⁸.

Sea level would rise to 80 cm above 2000 by 2100, only 5 cm above 1.5°C projections, thus resulting in comparable impacts. Long-term stabilisation at 2°C warming however implies a continuous sea level rise for centuries, with levels to approach 3 m by 2300³⁰. The threshold for the Greenland ice sheet to irreversibly melt is now estimated to be 1.6°C above preindustrial, compared to the IPCC AR4 estimate of 3.1°C³⁹.

2.1.4 4°C

Current emission trends and reduction pledges put the world on a trajectory towards a temperature increase of roughly 4°C by 2100. At such levels of warming, impacts are most severe, some of which might be beyond the limits of adaptation. The conditions of some of the most extraordinary heat waves experienced today will become the new norm and a completely new class of heat waves, with magnitudes never experienced before, will occur regularly^{40,41}. This will have severe but as yet un-quantified impacts on agricultural production and human health. Climate impacts become large enough to dominate changes in water stress, and the changes in water run-off projected for 4°C warming are roughly double those of a 2°C world⁴². The timing of warming is critical, as the world population is expected to grow until the second half of the 21st century. Under high-emission scenarios, the adverse impacts on water availability may thus coincide with maximum demand as the world population peaks³⁴.

The proportion of arid and semi-arid lands in Africa is likely to increase by 5% to 8%⁴³. When accounting for the amount of water needed to produce a certain amount of food in a given location, it is estimated that the global population living in water-scarce countries will double compared to today⁴⁴. Globally, drought disaster-affected areas in major crop-sowing areas are predicted to increase three-fold (from 15.4% to 44.0%) in 2100¹⁴. Crop yields for maize are expected to decrease between -13% and -23% and for beans between -47% and -87%, implying that “[...] the kind of changes that would occur in a 4°C world would be way beyond anything experienced in recent times”⁴⁵. Wheat production is likely to disappear from Africa by 2080⁴³, while millet yield in Sahelian Africa is projected to decrease by 40%⁴⁶.

In a 4°C world, climate change may become the dominant driver of ecosystem shifts, surpassing habitat destruction as the greatest threat to biodiversity^{47,48}. Due to ocean acidification, corals around the world are likely to start dissolving above 550 ppm CO₂⁴⁹. The Amazonian forest area is expected to contract to 25% of its original size³⁸ and up to 30% of other tropical rainforests, in central Sumatra, Sulawesi, India and the Philippines, is threatened by forest retreat³⁸. In Africa, 25%–42% of plant species could lose all suitable range by 2085⁵⁰. The interactions between impacts of climatic change, human actions (like deforestation), and forest responses (like fire) represent potential positive feedbacks that could lead to widespread Amazon forest degradation or loss⁵¹. Substantial loss of tropical forest would release large amounts of carbon dioxide into the atmosphere, which would accelerate climate change further. Between 2°C and 3°C of global-mean warming the global carbon sink provided by terrestrial plants is actually expected to strengthen, due to the CO₂ fertilisation effect, but it saturates above 3°C⁵².

Climate change has the potential to catalyse rapid shifts in dynamic, out-of-equilibrium ecosystems, such as sudden forest loss or regional loss of agricultural productivity due to desertification⁵³. The ramifications of these shifts would be far-reaching, ranging from extensive loss of biodiversity and diminished land cover, through to loss of ecosystem services⁵⁴. Ecosystem degradation diminishes biodiversity, which decreases the overall stability of the ecosystem again. Recent work on competition and habitat suggests that models generally underestimate the impact of climate change on biodiversity⁵⁵. 4°C warming by 2100 would likely result in global temperatures stabilising at 6°C above pre-industrial over the next few centuries⁵⁶. The most recent geological analogue for a 6°C world, the Palaeocene-Eocene thermal maximum 55 million years ago, saw a period of rapid global change, though still at a slower pace than projected for a future 4–6°C world⁵⁷. No paleo-analogue exists for the rapid warming projected under unmitigated climate change and it is fair to say that this will lead at least to widespread extinctions in ecosystems that are shown to have happened 55 million years ago⁵⁸.

Sea level rise (SLR) would exceed 1 m by 2100³⁰, with possibly up to 20% higher regional values⁴¹, while post-2100 sea level is hard to project, due to large knowledge gaps in understanding of the response of the ice caps to such strong warming. The potential impact of 1m sea level rise or more would be severe, with the real risk of the forced displacement of up to 187 million people over the century (up to 2.4% of global population)⁵⁹. East Asia, South-east Asia and South Asia would be most affected with an expected 53–125 million people displaced. The Small Island States, Africa and parts of Asia are the most likely to see coastal abandonment as the likelihood of successful protection measures is lowest here. Coastal cities in developing regions are especially vulnerable to SLR, due to high population densities and the often-inadequate urban planning and coastal protection. Including demographic information, Brecht et al.⁶⁰ estimate the future impact of climate change on storm surges that will strike coastal populations, economies, and ecosystems. They identify 10 Asian cities that account for 50% of the future exposure of SLR with over 40% falling on Manila, Karachi, and Jakarta alone. In Africa, countries with the highest total impacts under a 126 cm SLR scenario are

Egypt, Mozambique and Nigeria with respectively 8, 5 and 3 million people displaced annually⁶¹.

The frequency of the most damaging (category 4 and 5) Atlantic tropical cyclones is projected to nearly double by the end of the 21st century⁶². New research shows mortality risk depends on tropical cyclone intensity, exposure, levels of poverty and governance⁶³.

2.2 Ocean acidification^c

The previous section focused on impacts projected for different levels of global warming. However, the atmospheric CO₂ concentration has surpassed 380 ppm recently, which has not only led to climate change, but also to increased absorption of CO₂ by the oceans and an increase in the ocean's acidity, estimated at a reduction of 0.1 units of pH since pre-industrial⁶⁴. A lower pH value indicates higher acidity and since pH is a logarithmic scale, a reduction of 0.1 represents approximately a 30% increase in acidity. Higher acidity of ocean waters leads to reduced availability of calcium carbonate (aragonite), the resource vital for coral species and ecosystems to build skeletons and shells. Reduced reef calcification due to acidification has been observed in the last few decades⁶⁵⁻⁶⁷. Especially vulnerable are warm-water coral reefs, cold-water corals and ecosystems in the Southern Ocean. Identified impacts of reduced pH on these systems are a reduction in coral calcification (reduced growth), coral skeleton weakening and strong temperature dependence, the latter potentially increasing the risk of bleaching due to the rising temperature of surface waters⁶⁸.

IPCC AR4 projections for SRES scenarios indicate a further increase in the ocean's acidity of 0.14 to 0.35 units of pH over the 21st century⁶⁴, equivalent to an increase in acidity of 80–180% since pre-industrial times. A recent review shows that the anthropogenic rate of carbon input into the oceans appears to be greater than during any of the ocean acidification events identified so far over the geological past, dating back millions of years and including mass-extinction events⁶⁹. Recent research estimates that if atmospheric CO₂ reaches 450 ppm, coral reefs around the world will slow down growth considerably and at 550 ppm will start to dissolve^{49,70}. The effects of acidification have already been observed and will gradually worsen as acidification increases. Hence, reduced growth, coral skeleton weakening and increased temperature dependence will start to affect coral reefs below 450 ppm. A deterioration of coral reefs will have negative impacts on dependent species, fisheries, coastal protection and tourism in many regions.

A scenario that is consistent with a 1.5°C warming limit may start to drop down to CO₂ concentration of 350 ppm by the end of this century. A recent assessment concluded a CO₂ level of below 350 ppm is required for the long-term survival of coral reefs, if multiple stressors are included, like high ocean surface-water temperature events, sea level rise and deterioration in water quality⁷¹.

c This section is adapted from Schaeffer, M. and B. Hare (2012) "Ocean Acidification: Causes and Consequences", Climate Analytics, 1 October 2010.

2.3 Overview of impacts^d

As mentioned in the introduction and explained in the previous sections, even limiting warming to 1.5°C will not prevent far-reaching impacts, particularly for vulnerable countries, like LDCs and SIDS, nor for vulnerable ecosystems, like coral reefs. Above 1.5°C, however, not only will gradually increasing impacts become worse, but parts of the Earth system might enter a different state, accelerated by some identified ‘tipping elements’, such as irreversible melting of the Greenland ice sheet and risk of Amazon dieback. The graphic illustration in Figure 3 provides an overview of some impacts and tipping elements across temperature levels.³ Can warming be limited to 1.5°C?

^d This section is adapted from Höhne, N., B. Hare, M. Schaeffer, M. Vieweg-Mersmann, M. Rocha, C. Chen, J. Rogelj, M. Mengel, M. Perrette (2011) “After Durban: Risk of delay in raising ambition lowers chances for 2°C, while heading for 3.5°C”, Climate Action Tracker – Climate Analytics, PIK, Ecofys, 11 December 2011.

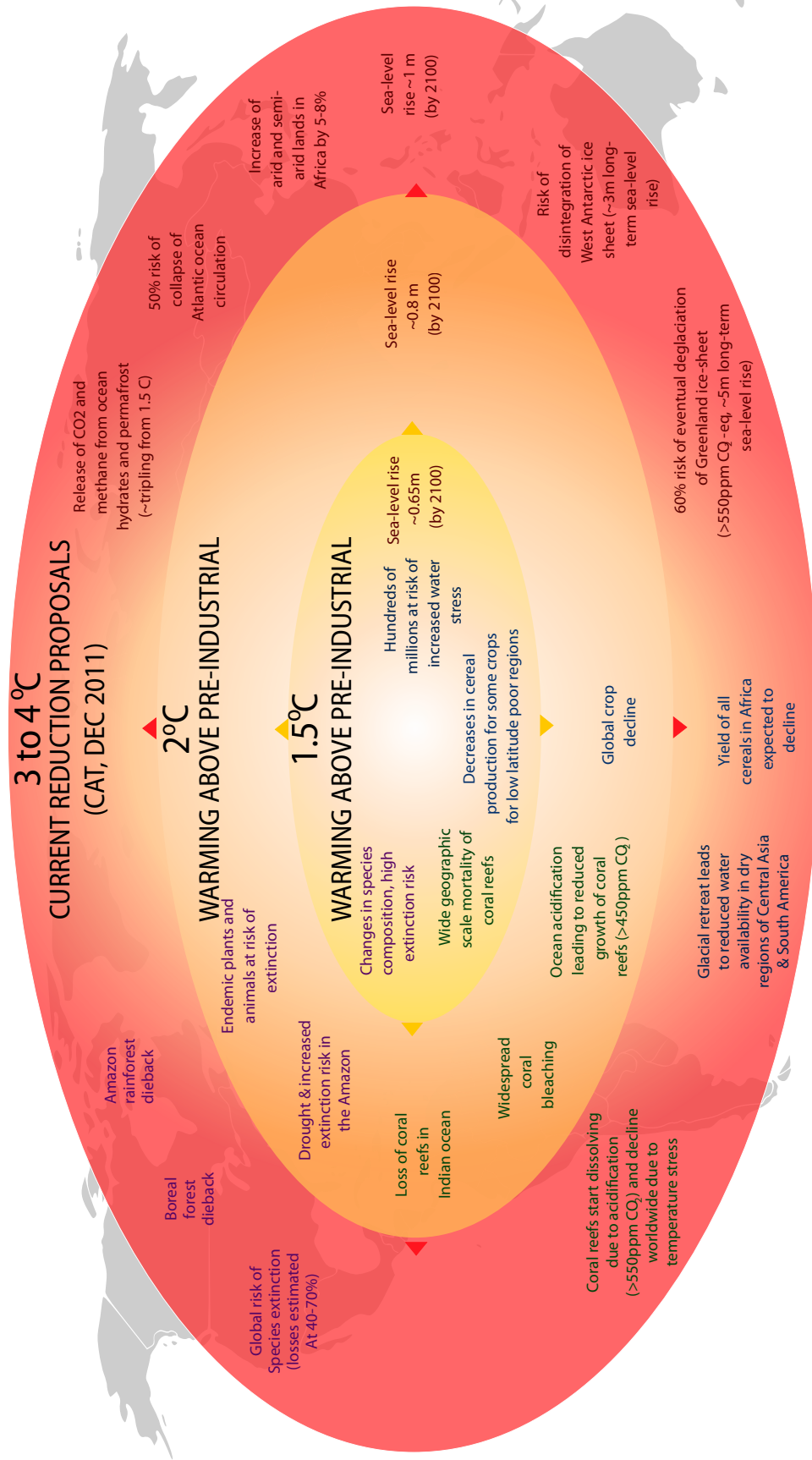


Figure 3. Overview of some of the impacts and tipping points at warming levels of 1.5 to 4°C above pre-industrial. Source: www.climateactiontracker.org

3 Can warming be limited to 1.5°C?

3.1 Geophysical feasibility of 1.5°C

Present-day global warming is about 0.8°C. If all emissions were to be eliminated immediately, delays in the climate system and abrupt changes in atmospheric radiative forcing would let warming continue to rise to a best-guess level of 1.2°C above pre-industrial, before embarking on a gradual decline (black dashed line in Figure 4).

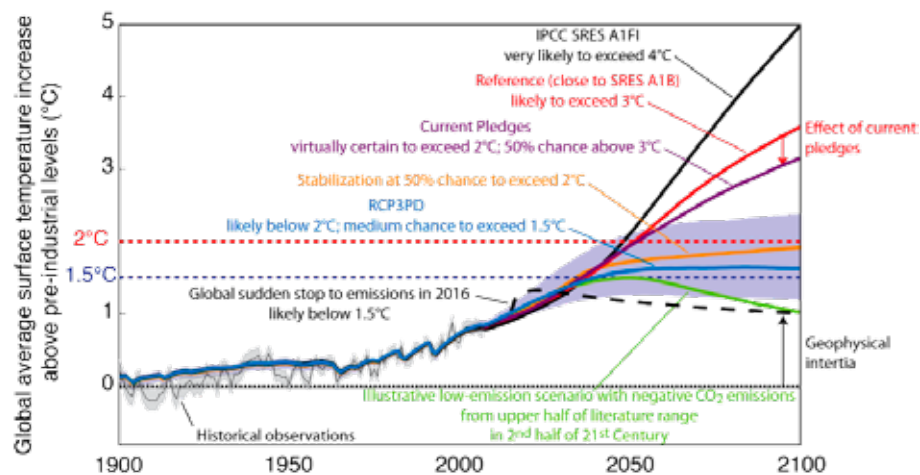


Figure 4. Median estimates (lines) from probabilistic temperature projections estimates for business-as-usual emission scenarios (SRES A1FI and Reference), as well as a wide range of mitigation scenarios holding warming below 2°C with a 50% chance or more^{30,72,73}. The 15–85% uncertainty range is provided for one scenario only to enhance readability.

Obviously, an immediate stop to all global emissions is infeasible, but in the long term, concentrations will only stabilise, if global CO₂ emissions were reduced to near zero⁷⁴. Delaying emission reductions results in higher cumulative emissions. Even if CO₂ emissions are brought down to zero after such a delay, the higher cumulative emissions lead to both concentrations and warming stabilising at a higher level.

The slow response of concentrations and warming might also be turned into an advantage. It would take decades to centuries for human-induced temperature increase to fully stabilise at a level indicated in Figure 1, for example at more than 2°C for a concentration of 450 ppm CO₂eq. Until this full temperature response is reached, warming remains below the level achieved in full equilibrium. This delay means there is an option for emissions and concentrations to peak and decline, aiming to bring down concentrations from a peak level, before the entire climate system has time to warm up to that peak. If concentrations go down far enough and quickly enough, warming might even decline within the 21st century, as illustrated by the hypothetical sudden-stop scenario. Geophysically speaking, there is therefore no reason to see 1.5°C as beyond reach.

For 2005 the IPCC AR4 estimated that the total CO₂eq concentration of all long-lived greenhouse gases amounted to about 455 ppm CO₂-equivalent, although with the cooling effects of aerosols and other air pollutants taken into account the net greenhouse gas concentration was estimated to be in the range 311 to 435 ppm CO₂eq. As shown in Figure 1 in the Introduction, a warming limit of 1.5°C requires concentrations below 400 ppm CO₂eq. Any mitigation pathway aiming to achieve stabilisation at 350 ppmv CO₂-equivalent taking into account all Kyoto gases (CO₂, CH₄, N₂O and F-gases) hence necessarily involves a peak-and-drop concentration profile, dropping down from current concentrations to a value around 350 ppm CO₂eq.

3.1.1 Role of air pollutants^e

Recent publications⁷⁵⁻⁷⁷ have suggested that so-called Short-Lived Climate Forcers (SLCFs) might help to reduce near-term warming and stay below 2°C. The term SLCFs has evolved to cover, for example, methane, HFCs and air pollutants like black carbon and organic carbon. The relatively short lifetime in the atmosphere ranges from 12 years (methane) to a few days or weeks (black carbon, organic carbon, etc.).

Non-CO₂ measures must never be interpreted as a means for “buying time” to allow delayed reductions in CO₂. This can be shown by considering a scenario where the full implementation of all air-pollutant measures as identified by Ref 75-77 is accompanied by a 10-year delay in CO₂ and related sulphur reductions. After a delay to 2030, CO₂ emissions^f are reduced rapidly to ultimately reach the same level as the original low-emission pathway by 2100. In the short term, warming is lower (up to 0.1°C by the 2020s) than in the original low-emission scenario. This reduced warming is mainly the result of higher SOx emissions, which have a cooling effect, associated with the delayed reductions in CO₂. However, if a high value for present-day radiative forcing of BC is assumed, cooling from lower BC and related emissions roughly equals that of the higher SOx emissions. However, such a pathway of accelerated pollutant measures combined with delayed CO₂ measures has two important disadvantages, even if we assume a high present-day level of BC forcing.

Firstly, the probability of exceeding a 2°C warming in the 21st century more than doubles from 20% to 50%. Median warming is projected to be 0.3°C higher in 2100 and, crucially, given the slow removal of CO₂ from the atmosphere, this effect is set to linger for centuries. Note that this delayed-CO₂ pathway still includes fully all of the incremental effects of reductions in HFCs, CH₄ and others of the original low-emission pathway and the higher warming by 2100 is solely the effect of the 10-year delay in CO₂ measures.

e This section is adapted from Hare, B., M. Schaeffer, M. Rocha, J. Rogelj, N. Höhne, K. Blok, K. van der Leun and N. Harrison (2012) “Closing the 2020 emissions gap: Issues, options and strategies”, Berlin, Germany, Climate Analytics and Ecofys.

f SOx emissions would follow this downward path

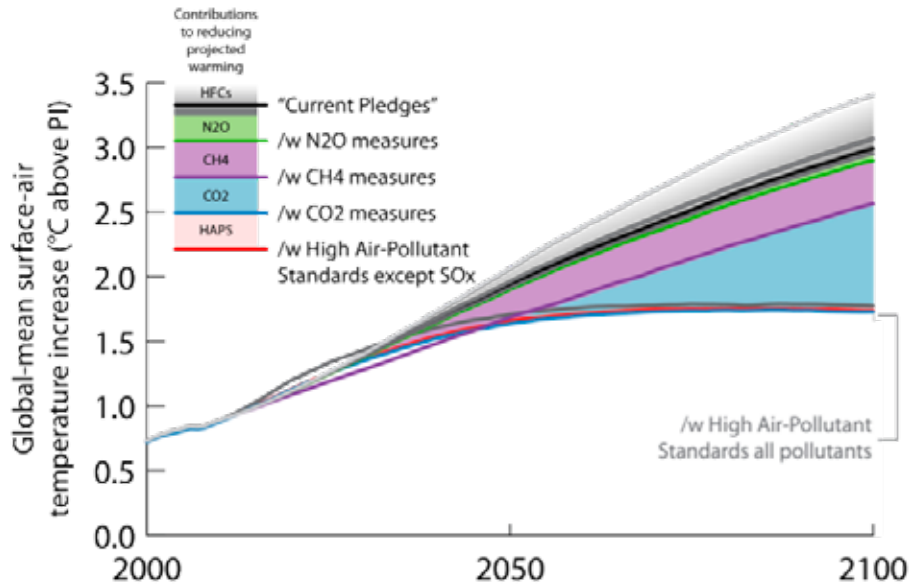


Figure 5. Incremental effects of emissions reductions for different greenhouse gases HFCs, N₂O, CH₄, CO₂, as well as air pollutants. The /wCO₂ measures include only those air pollution reductions consistent with energy system changes. This can be compared to low CO₂ emissions with high air pollutant standards including SO_x (grey) and without additional SO_x controls (red). The difference between the red and the blue curves is thus due mainly to additional action on BC, on top of those associated with the low-carbon energy-system transformation. The difference between the grey and the red is essentially the effect of lower SO_x emissions under a high air-pollutant standards scenario.

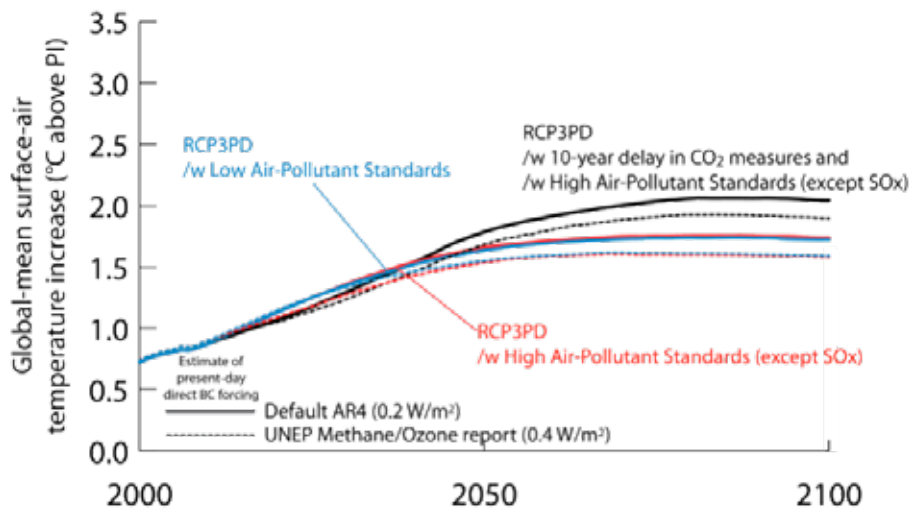


Figure 6. Global warming projections for low-carbon pathway RCP3PD (blue line) and a scenario where CO₂ reductions are delayed until 2030 but with large reductions in black carbon and related air pollutants, according to a shift from Low to High Air-Pollutant Standards, which exclude sulphur (black). In the delay case, CO₂ and SO_x emissions follow a scenario implied by current reduction pledges until 2030, after which they are reduced rapidly towards RCP3PD levels by 2100. The red line shows the relative cooling benefits of only implementing accelerated air-pollutant reductions, without a delay in CO₂ measures. For comparison, the dashed lines show results for the same scenarios, applying present-day direct radiative forcing from BC as assumed in the UNEP Methane and Ozone reports^{76,77}, which is about double the estimate in IPCC AR480. Such higher forcing estimates would imply that BC measures have a larger cooling effect (compare dashed red with dashed blue line), but these are as temporary as in the default (AR4) cases.

Secondly, energy-related CO₂ reduction rates between 2030 and 2050 on average need to be 2.4% of 2010 levels per year, rather than the 1.5% per year in the original low-emission pathway with early CO₂ measures. Without these higher reduction rates to “catch up”, the CO₂ concentration and warming by 2100 will be even higher. From a multi-decadal perspective, delay scenarios have been shown to be riskier, requiring faster CO₂ reductions after a 10-year delay, and generally too expensive and/or technically infeasible^{78,79}.

3.2 Energy-economic scenarios^g

Since the publication of IPCC’s AR4, a range of cost estimates was published for mitigation pathways leading to greenhouse gas concentrations in, or below, the lowest-emission category assessed in AR4. These studies have produced feasible pathways leading to stabilisation levels down to 400 ppm CO₂eq.

Most energy-economic models are able to achieve low emission levels, but this crucially depends on:

- Early and globally concerted mitigation, emission reductions implemented from 2013 onwards and global emission peak by 2020.
- Rapid up-scaling and feasibility of large-scale bio energy, and availability of forest sinks.
- High rates of energy efficiency improvements.
- Availability of carbon capture and storage technologies (CCS).

A recent study published by the Energy Modelling Forum (EMF) explored these key determinants of the feasibility of low-emission scenarios. The study re-confirmed that low emissions could be rendered infeasible, if no globally concerted mitigation is achieved and/or emission concentration profiles are not allowed to reach a temporary peak before declining, the latter depending on the availability of CCS technology to achieve negative emissions later on in the 21st century.

“Where climate-action cases could not be modeled solely for model solution or high initial price reasons, this is an indication of particularly high rates of change in the energy and other climate-related sectors, which may prove politically difficult to produce, but does not imply a lack of physical feasibility.”⁸¹

3.2.1 Role of negative emissions: biofuel-energy with carbon capture and storage

The UNEP Gap reports identified a range of energy-economic scenarios that achieve 2°C with a probability higher than 66% and a return to below 1.5°C by 2100 with a probability of 50%. Until the 2030s, these two classes of scenarios overlap, but a 1.5°C scenario requires deeper reductions in the rest of the 21st century. Constrained by real emissions until 2010 and energy-economic reduction potential until the 2020s, the 1.5°C scenarios necessarily

^g This section is adapted from Schaeffer, M. and F. Fallsch (2010) “Feasibility of low-emission pathways”, Berlin, Germany, Climate Analytics, 11 June 2010.

require net-negative CO₂ emissions in the second half of the 21st century (Figure 7). The later the emissions peak, the more CO₂ needs to be removed starting around the 2050s (Figure 8).

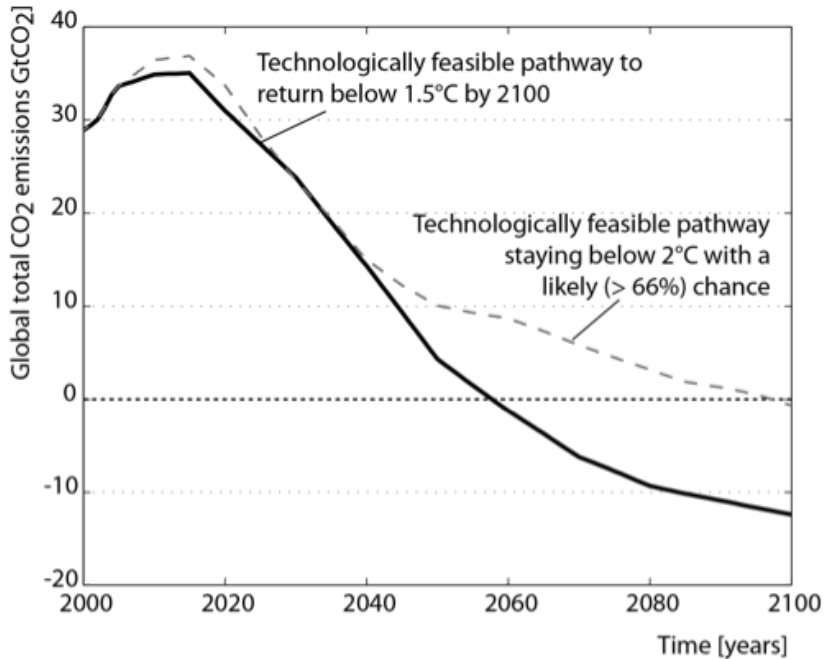


Figure 7. CO₂ emissions in a 1.5°C scenario overlap with a 2°C scenario until the 2030s, but require deeper reductions in the rest of the 21st century.

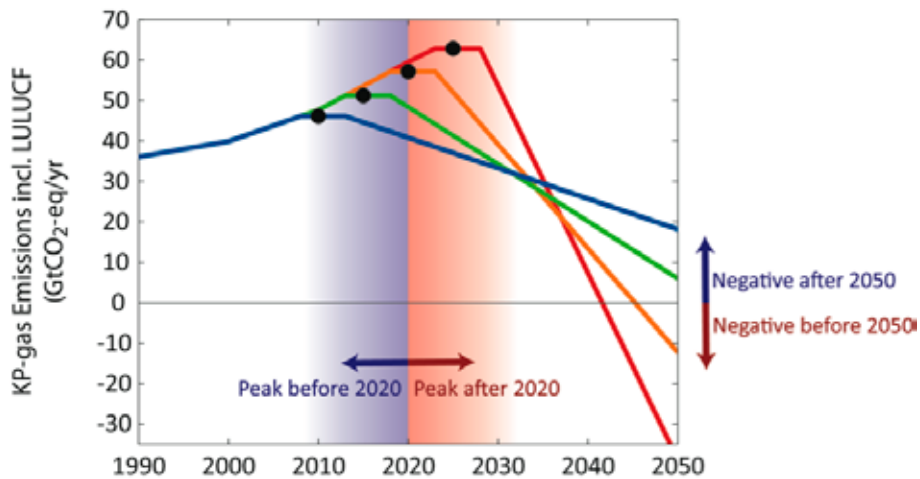


Figure 8. The effect of a delay in 2020 reductions, but keeping fixed cumulative emissions in the period up to 2050 (hence a fixed probability of exceeding temperature targets) is to increase the required reduction rate up to 2050 and deepen the reductions needed by 2050. The blue line is comparable to a scenario with a 50% reduction below 1990 by 2050, as is the blue line in Figure 4. A longer delay is illustrated here by following business-as-usual paths for a longer time (in this case IPCC SRES Marker scenario A2).

Due to slowly responding carbon pools in the Earth system, a large part of emitted CO₂ stays in the atmosphere for centuries, which is why emissions need to be reduced to near zero for stabilising concentrations, as mentioned above. However, this also means that concentrations decrease only slowly, unless CO₂ is taken out of the atmosphere by human interventions. The main technology foreseen by the present generation energy-system models

to achieve this is known as Biomass Energy Carbon Capture and Storage (BECCS)^h. As biomass takes up carbon from the atmosphere through photosynthesis, extracting the CO₂ from biomass energy systems and storing it underground, it effectively produces useful forms of energy for society (electricity) while taking CO₂ out of the atmosphere – a negative emission. This is not necessarily an example of geo-engineering: ‘cleaning up the mess’ through an energy-system transformation involving BECCS is no more a form of geo-engineering than ‘making the mess’ by fossil-fuel consumption was in the first place. What is also important to realise is that CO₂ removal helps solve the issue of ocean acidification, which is not addressed by geo-engineering options that intervene in warming, for example by reducing the solar radiation input into the Earth system.

Growing biomass has the potential to sequester carbon from the atmosphere in terrestrial ecosystems, by changing agricultural practices and forest management. In addition biomass in the form of biofuels is seen as a near-CO₂-neutral substitute for fossil fuels in both the transport and power sectors. If the latter use is combined with CCS, the system has the potential of generating negative net CO₂ emissions over the full lifecycle of the process. In this system of Biomass Energy with Carbon Capture and Storage (BECCS), CO₂ sequestered during biomass growth before harvest is only partly re-released to the atmosphere, the other part being stored for geological timescales.

The extent of the ethical, political, ecological and legislative obstacles to the required large-scale overhaul of current land-use practices are under debate, but the technical potential may be sufficient to draw down CO₂ concentrations back to current levels before the end of the 21st centuryⁱ. From an engineering perspective, a coupling of two systems is required, both of which are currently being explored in numerous projects. Various bio-energy systems are already being applied commercially, or have reached the commercial implementation phase. Exploration of CCS technology and further scientific and engineering analysis of full CCS lifecycle emissions and costs need expansion. The latter is also crucial if a more industrial approach to reach negative emissions is to be deployed. Direct air capture^j of CO₂ by chemical processes is seen by some as an ultimate ‘back-stop’ technology to bring down CO₂ concentrations below dangerous levels as soon as observational evidence and scientific advancement deem this necessary. Current projections of costs are high, but they may be higher still if a comparably low level of

h For example: Azar et al. (2006) “Carbon Capture and Storage From Fossil Fuels and Biomass – Costs and Potential Role in Stabilizing the Atmosphere”, *Climatic Change* 74 (1), 47-79; Knopf et al. (2008) “Report on first assessment of low stabilisation scenarios”, D-M2.6, PIK, Potsdam, Germany; Rao et al. (2008) “IMAGE and MESSAGE Scenarios Limiting GHG Concentration to Low Levels”, Interim Report IR-08-020, IIASA, Laxenburg, Austria.

i For an overview of the energy systems involved and their potentials in a strategy for drawing down the CO₂ concentration, see e.g. Read, P. (2008) “Biosphere carbon stock management: addressing the threat of abrupt climate change in the next few decades: an editorial essay”, *Climatic Change* 87, 305-320, and comments on Read’s paper by Rhodes and Keith (2008) “Biomass with capture: negative emissions within social and environmental constraints: an editorial comment”, *Climatic Change* 87, 321-328

j For an informal discussion, see Jones, N., *Nature* 458, 30 April, 2009, 1094-1097.

CO₂ concentration needs to be achieved without such technologies. As with bio-energy systems, air capture requires a combination with CCS to achieve negative emissions.

There is a need for an active research programme into the technology choices for limiting CO₂ concentrations to low levels, in order to identify the potential synergies and conflicts between fossil carbon capture and storage, biomass carbon capture and storage, renewable energy systems and energy efficiency. The rate of growth of renewable energy in recent years has been extraordinary and is indicative that in many markets renewable energy (in the form of wind energy) is one of the best short-term options for capacity expansion in the electric supply area. With declining prices for photovoltaics in many markets there is an expectation of grid parity within the next 5 to 10 years, which could revolutionise the market in this area. A scaled-up research programme covering technological, economic and legislative and regulatory issues should not conflict with the short-term need to introduce technologies that reduce emissions.

In addition to the legislative issues raised for CCS in general, a number of social, legal and legislative issues are relevant in particular for the combination of CCS with biomass in BECCS systems^k:

- The recent biofuels boom demonstrates two sides of the issue: the potential of a short-term, large-scale deployment of bio-energy, while on the other side potentially inducing fundamental social problems, including price distortion on the world food markets and environmental concerns. The latter pose legislative challenges of regulating competing land uses, including production of food and fodder, and nature conservation. The technological challenge here is to move away from the present generation of biomass energy technologies to those based more on woody plants that do not compete for food production in the same way as first-generation biomass systems.
- Given the geographic distribution of productive land, a large-scale deployment of biomass production would likely require substantial areas of land in developing countries. The implementation of an effective BECS system requires commercialisation of wood-based crop technologies for energy production that would not adversely affect food production or water supply, as well as the carbon capture and storage technology. Beyond the middle decades of this century biomass carbon capture and storage appears to be necessary to achieve low CO₂ concentrations. If there are to be substantial negative emissions technologies introduced after the 2050s there would need to be substantial investment in research, development, demonstration and commercialisation well before then. Hence there would need to be a scaling up of investment in research and development of CCS technologies, and into environmentally sustainable ways of growing, producing and transporting biomass fuels. In order to develop the required scale there would need to be an introduction into the energy system of technologies designed to achieve

^k For a discussion, see Rhodes and Keith (2008) "Biomass with capture: negative emissions within social and environmental constraints: an editorial comment", *Climatic Change* 87, 321-328

negative CO₂ emissions within a few decades. The role and potential of this technology would need to be set against a role for fossil carbon capture and storage to verify any conflicts or synergies between fossil and biomass systems. In the short run (2020s to 2030s), biomass carbon capture and storage will not play a significant role in reducing emissions to the atmosphere, although what happens in this period may be quite fundamental in the longer term for reducing CO₂ concentrations quickly, depending on the ability to scale up this technology.

The true technological feasibility of negative emissions technology is at present not well-established. There is a need for an upgraded research programme into all aspects of this technology, including the policies and measures required to introduce this into energy markets and to investigate the synergies and potential conflicts with biomass and fossil carbon capture and storage technologies.

Whilst the successful introduction of carbon capture and storage technologies would help lower CO₂ emissions in the longer term, an emerging risk for climate mitigation policies in the short term is posed by demands for the large-scale approval of new coal-fired power plants on the basis that these may be retrofitted later with CCS technology as soon as this technology will have proven viable on a large scale. The latter is not without doubt and a failure of large-scale implementation of CCS in the short term will leave the electric power system depending on newly-constructed coal-fired plants without CCS for another 30 or 40 years of operation, when this could have been avoided through reliance at present on an expansion of renewable energy capacity and energy efficiency in many cases. Another concern with CCS outfitted plants, as well as retrofitting, is that the CCS capacity might be filled up with carbon captured from fossil-fuel plants, whereas this capacity might be needed later for BECCS systems.

3.2.2 Role of nuclear energy

A phase-out of nuclear capacity, as envisioned for Germany, offers a window of opportunity, if it is combined with a smart investment strategy reaching full decarbonisation by 2050. Various studies show that a transition to a completely renewable power infrastructure is possible within a relatively short time frame^l. Japan might still pursue this road as well, as was stated by top government spokesman Yukio Edano in the wake of the Fukushima incident, although there have been mixed signals on their future strategy since:

“Pursuit of solar power, bioenergy and other clean energy sources will be a key pillar of the government’s reconstruction strategy to be drawn up for areas hit by a massive quake and tsunami following the country’s worst nuclear accident”^m.

If the opportunity is used to transform the power sector, the effects on CO₂ emissions will be positive in the medium and long term. For Germany, for example, various studies come to the conclusion that a nuclear-free power

^l See for example: Matthes, F. et al. (2011). “Schneller Ausstieg aus der Kernenergie in Deutschland. Kurzfristige Ersatzoptionen, Strom- und CO₂-Preiseffekte”; Schwartzman, P.D. and D.W. Schwartzman (2011). A Solar Transition is Possible.

^m Kyodo News, 29 March 2011. <http://english.kyodonews.jp/news/2011/03/81780.html>

sector is possible to achieve in a very short time, but could also benefit climate by strengthening efforts in energy efficiency and renewable energy.ⁿ

The opportunity is even greater where this change in strategy leads to a replacement of newly planned nuclear capacity. Due to the high investment cost of new nuclear plants the same investment saving could be redirected towards low-carbon power sources, smart grid infrastructure and demand management systems, and produce larger emissions reductions for the same investment. Each dollar spent on a new reactor buys about 2–10 times less carbon savings, 20–40 times slower, than spending that dollar on the cheaper, faster, safer solutions: efficient use of electricity, making heat and power together in factories or buildings ("cogeneration"), and renewable energy^o. Nuclear power is also one of the few energy technologies to exhibit negative learning, in other words, increasing costs with time rather than decreases^p.

The characteristics of nuclear energy infrastructure and investments discussed here play a role in energy-economic modelling of cost-optimal 21st century mitigation scenarios. Nuclear energy is one in a range of non-fossil fuel options in most emission-reduction scenarios aimed at limiting emissions to a level consistent with 2°C warming. For example, in IEA's "Energy technology perspectives 2010", nuclear energy provides 6% of the reductions from the baseline needed by 2050 to reach a 2°C-consistent scenario^q. A wide inter-comparison of energy-economic models and scenarios^r found that

"Nuclear power does not play an important additional role in mitigation scenarios in any of the models beyond the role it plays in their baselines where nuclear energy is attractive in most models; fixing nuclear power to its baseline values leads only to a marginal increase in costs. With a phase out of nuclear, however, costs do increase. However, this is less than with an economically severely limited CCS potential".

Hence, required emission reductions are possible without nuclear energy, but whether they are achieved, depends on structural long-term choices: for equal reductions at somewhat higher costs, or weakened mitigation at equal costs. A recent economic analysis showed this assessment to hold in an energy-economic modelling framework, showing that the economic impact of imposing a stringent carbon budget on the economy is the first-order effect, and much larger than restrictive nuclear power policies⁸².

n Greenpeace Germany (2011). "Der Plan: Ein aktuelles Energiekonzept für Deutschlands Atomausstieg bis 2015"; Matthes, F. et al. (2011)

o see e.g. Amory Lovins at http://www.huffingtonpost.com/amory-lovins/nuclear-power-fukushima-_b_837643.html

p Grubler, A. The costs of the French nuclear scale-up: A case of negative learning by doing. *Energy Policy* 38, 5174-5188 (2010)

q IEA. (2010). *Energy technology perspectives*. International Energy Agency (IEA), Paris, France, 18 pp.

r Edenhofer, O., Knopf, B., Barker, T., Baumstark, L., Bellevrat, E., Chateau, B., Criqui, P., Isaac, M., Kitous, A., Kypreos, S., Leimbach, M., Lessmann, K., Magne, B., Scricciu, S., Turton, H. and van Vuuren, D. (2010). "The Economics of Low Stabilization: Model Comparison of Mitigation Strategies and Costs", *The Energy Journal* 31(Special Issue): 11-48.

3.3 Overview of climate response to emission scenarios

The previous sections provided a review of climate-system constraints and energy-economic constraints to achieve 1.5°C. In summary:

- Holding global warming below 2°C is physically possible.
- Likewise, returning warming to below 1.5°C by 2100 is physically possible, after exceeding it temporarily in the 2050s.
- Technologically and economically feasible scenarios that achieve the 1.5 and 2°C targets have been published in the scientific literature.
- In the short term, scenarios consistent with 1.5°C and 2°C have been shown to overlap until the 2030s. Afterwards, stronger emission reductions are required for 1.5°C.
- Emission reductions required by 2020 to keep below 1.5°C and 2°C are feasible and can be achieved at moderate cost, requiring only well-known technology options.
- The reductions are most feasible if action starts before 2015: the longer the delay, the more difficult and expensive.
- Important technologies in post-2020 pathways identified as required to increase the probability to stay below 2°C and return to below 1.5°C need much further consideration and research.
- Given the uncertainties in the large-scale viability of technological options, a delay in action is further risky by reducing the future flexibility in deploying all technological options: the longer the delay, the less luxury the world has to NOT deploy certain technologies.

To put the scenarios discussed above into perspective, we show in Figures 6–9 projections for other global-mean climate indicators, using the same emission scenarios used for the warming projections in Figure 5.

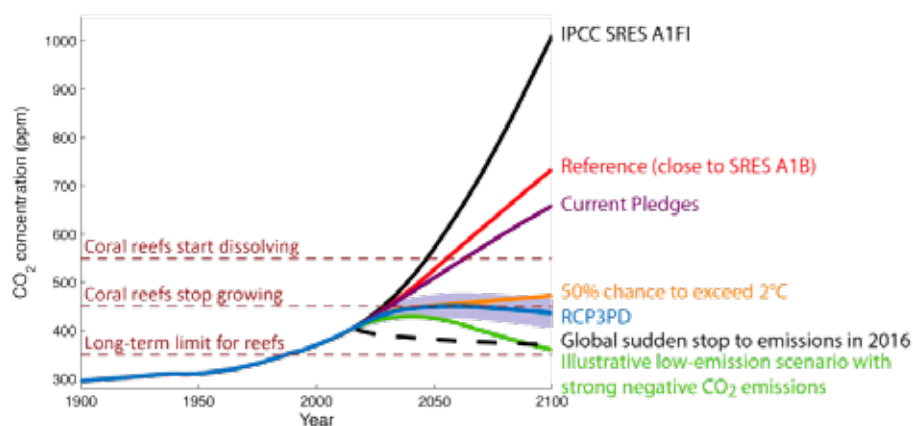


Figure 9. As Figure 4 for atmospheric CO₂ concentration. Coral reef survival limits from Silverman et al. (2009) and Veron et al. (2009)^{49,71}.

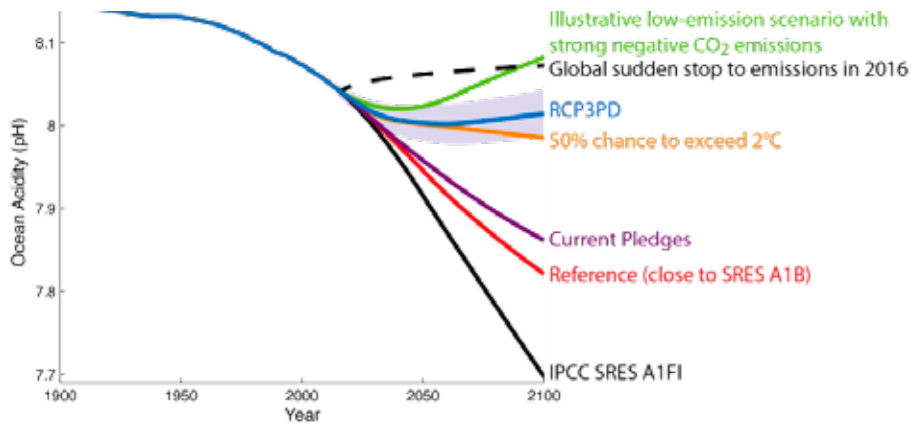


Figure 10. As Figure 4 for surface-ocean pH. Lower pH indicates more severe ocean acidification, which inhibits growth of calcifying organisms, including shellfish, calcareous phytoplankton and coral reefs. Method for estimating pH from Bernie et al. (2010)⁸³.

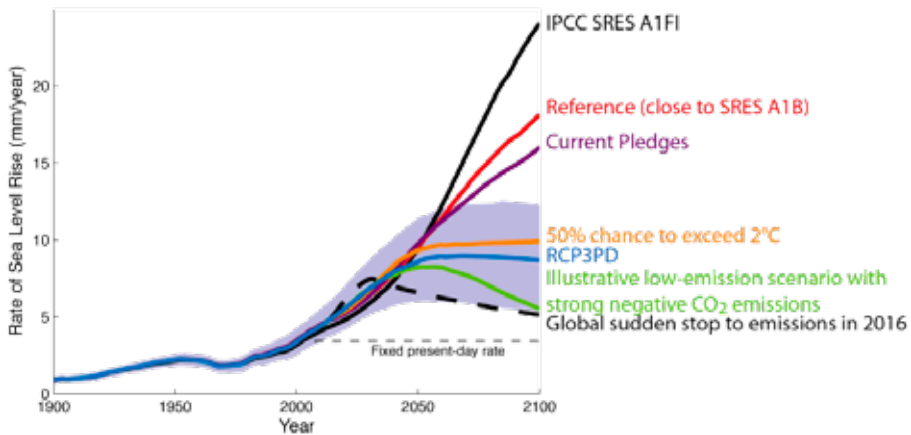


Figure 11. As Figure 4 for annual rate of global-mean sea level rise. The indicative/fixed present-day rate of 3.3 mm.yr⁻¹ is the satellite-based mean rate 1993–2007⁸⁴.

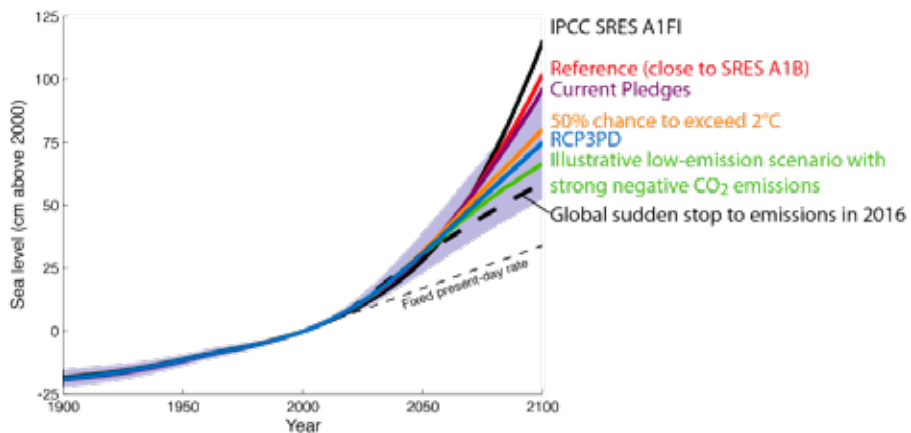


Figure 12. As Figure 4 for global-mean sea level rise above 2000 levels. “Fixed present-day rate” illustrates sea level rise in the 21st century if hypothetically the mean rate of change equals the rate observed by satellites over 1993–2007⁸⁴.

4. Ambition level of emission reduction proposals

4.1 2020 ambition of pledges and emissions levels consistent with 1.5°C

As explained in the previous section, 1.5 and 2°C pathways overlap until the 2030s. In recent years, UNEP coordinated scientific reports on global 2020 emission levels^s. The scientists involved in the reports estimated that a large gap exists (the ‘Emissions Gap’). This gap is between, on the one hand, the 2020 global emission level implied by current emission reduction pledges by countries and, on the other hand, the lower 2020 global emission level required to put the world on a feasible long-term emission pathway to hold warming below 2°C. The reports further showed that until after 2020 this 2°C pathway overlaps with a pathway that achieves a warming limit of 1.5°C in the long term, as mentioned above.

The Emissions Gap was estimated as 8–13 GtCO₂e, which shows unambiguously that currently proposed emission reductions for 2020 are insufficient to put the world on track for 1.5 or 2°C. The report further noted that avoiding double-counting of CDM credits is required to prevent the gap from increasing by up to 2 GtCO₂e. CDM double-counting results when a single emission reduction achieved by a particular CDM project is claimed as a reduction by the developed country providing the funding, as well as by the developing country that hosts the project.

The 2020 Emissions Gap refers to the further reductions needed to put the world on track for a probability of staying below 2°C of at least 66%, or “likely” in IPCC terminology. The UNEP report states that the higher the emissions in 2020 are, the more expensive the reductions will be afterward, and the more one has to rely on technologies which are not yet established on a large scale. The recent IEA “World Energy Outlook 2011” arrived at a similar conclusion and states that: “Delaying action is a false economy: for every \$1 of investment avoided in the power sector before 2020 an additional \$4.3 would need to be spent after 2020 to compensate for the increased emissions.”

4.2 Options to close the 2020 Emissions Gap

UNEP, the International Energy Agency^t and others, have provided clear guidance on how to close the 2020 Emissions Gap:

- 1) Increase the global share of renewables from an estimated 10% at present to 15% by 2020. This will help to close the Gap by 4 GtCO₂.
 - Increase further to a 20% share to close the Gap completely.

s UNEP (2010) “The Emissions Gap Report. Are the Copenhagen Accord Pledges Sufficient to Limit Global Warming to 2° C or 1.5° C? A preliminary assessment”, United Nations Environment Programme, Nairobi, Kenya; UNEP (2011) “Bridging the Emissions Gap. A UNEP Synthesis Report”, United Nations Environment Programme, Nairobi, Kenya; UNEP (2012) “Bridging the Emissions Gap 2012. A UNEP Synthesis Report”, United Nations Environment Programme, Nairobi, Kenya.

t IEA (2011) “World Energy Outlook 2011”, Paris, France

- 2) Intensify energy efficiency improvements, which would have a major impact on global energy and climate trends and would postpone a lock-in in emissions from 2017 to 2022.
- 3) Reduce subsidies for fossil fuels to decrease global emissions by 2 GtCO₂ by 2020 (Figure 13)
 - Fossil-fuel consumption subsidies worldwide amount to \$409 billion in 2010 and may grow to \$660 billion in 2020. Eliminating subsidies reduces fossil-fuel demand and emissions.
 - Global renewable-energy subsidies were only \$66 billion in 2010.
- 4) In the international negotiations context:
 - Implementing the more ambitious “conditional” pledges. This would reduce the gap by 2 GtCO₂e.
 - Minimise the use of lenient Land Use, Land Use Change and Forestry (LULUCF) credits and surplus emission credits. This would reduce the gap by around 3 GtCO₂e.
 - Minimise the use of the surplus Assigned Amounts from the 2008-2012 Kyoto period. This would reduce the gap by 1.8 GtCO₂e.
 - Avoid the double-counting of offsets and improving the additionality of CDM projects. This would reduce the gap by up to 1.5 GtCO₂e.
 - Reduce emissions from international shipping and aviation.

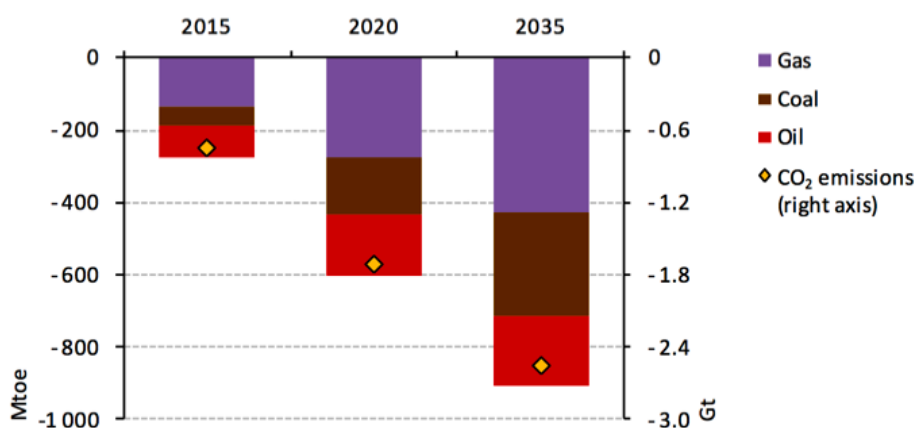


Figure 13. Impact of fossil-fuel consumption subsidy phase-out on global energy demand and CO₂ emissions, 2012–2035. Source: “Joint report by IEA, OPEC, OECD and World Bank on fossil-fuel and other energy subsidies: An update of the G20 Pittsburgh and Toronto Commitments”. Prepared for the G20 Meeting of Finance Ministers and Central Bank Governors (Paris, 14-15 October 2011) and the G20 Summit (Cannes, 3-4 November 2011).

4.2.1 Complementary measures

In the discussions on the Emissions Gap, several sources have suggested ‘complementary measures’ might help close the Gap, including measures on Short-Lived Climate Forcers (SLCFs) such as methane, HFCs and black carbon. Regarding methane and HFCs, a crucial piece of information on ‘complementary measures’ is whether the effects come unambiguously on top

of reductions achieved by current pledges, and lead to overall deeper reductions than these. If so, this will help, but there should be no objection against including such deeper methane or HFC reductions in the overall reduction pledges themselves, and thereby increasing the ambition of those pledges.

Reductions in black carbon and related air pollutants also have highly uncertain effects on climate and their long-term climate benefit is at best partially in addition to that achieved in a low-carbon development pathway (see Section 3.1.1). There are already large air-pollutant reduction benefits from the energy-system transformation required to reach a low-carbon development pathway, because the phase-out of fossil-fuel activities and technologies will eliminate co-emitted pollutants. Given the large associated health and other benefits of improved air quality, this reduces the net costs of CO₂ measures^{85,86}. By contrast, more rapid air-pollutant reductions, beyond those achieved from energy-system transformation alone, add relatively little to reduced warming, even when comparably rapid action on SO_x emissions is excluded. However, such deep reductions in air pollutants still have large benefits for human health and in other areas.

Although some complementary measures might help, if additional to current pledges, from the perspective of implementing effective mitigation strategies, a very unhelpful argument has been used relating to pollutant reductions, i.e. that such measures can be implemented to “buy time” to figure out how to act on CO₂. There is no lack of clarity about the energy-economic measures required to reduce CO₂, so buying time should not be necessary to “figure this out”. Worse, climate models show that even a delay of just 10 years in reducing CO₂ leads to warming after 2050 that is higher by an amount larger than any cut in short-lived forcers, now or in the future, would be able to compensate (see Figure 6). Without strong CO₂ reductions the warming goals considered here cannot be achieved. This is important to bear in mind as in some cases there is confusion about the role of non-CO₂ emissions in keeping to a 1.5 or 2°C pathway.

4.2.2 Ambition Gap or Participation Gap?

Without question, the effort that is required to close the global Emissions Gap will require political will from all countries. However, the stark reality of the Emissions Gap has prompted some UNFCCC delegations, including that of the USA, to put forward an argument to explain why the Emissions Gap is not really the key problem: Rather than an ‘Ambition Gap’, there is a ‘Participation Gap’: the required global 2020 reductions will be achieved if the Parties that have not taken on reduction pledges will do so.

Parties that have not yet put forward emission reduction targets account for about 20% of current global emissions. At maximum, a contribution to close the 2020 Emissions Gap of about 1 GtCO₂e can be expected from full participation of these Parties, if they pledge reductions at the maximum level of currently pledged ambition of already participating Annex I Parties, even with strict accounting rules. Clearly the 6–11 GtCO₂e ‘Ambition Gap’ is a much broader problem than the maximum estimated 1 GtCO₂e ‘Participation Gap’.

A good example to compare with is the USA, which by itself accounts for about 16% of current emissions. The current 2020 pledge of the USA amounts to 17% below 2005, which equals about 3% below 1990. This falls far short of the 25–40% reduction range estimated in IPCC AR4 to be required from Annex I Parties, and is also above their pledge of -7% below 1990 levels associated with the Kyoto Protocol, which the USA signed in 1997, but has never ratified. Compared to the USA's current 2020 pledge of 17% below 2005, the global Emissions Gap would be narrowed by 1–2 GtCO₂e just by strengthening the pledge of the USA alone to 25–40% below 1990.

4.3 2030–2050 and further

Beyond 2020, emission reductions will have to intensify, as apparent in Figure 7. For a 2°C pathway (with a 'likely' chance), global emissions need to be reduced by 2050 to about 50% below 1990, including emissions from deforestation and international aviation and marine transport, or 'bunkers'. The climate projections for such a pathway are illustrated in Figures 4 and 9–12 by the blue line.

For a 1.5°C pathway the reductions need to be deeper. How much deeper, however, depends on how fast one requires warming to drop below 1.5°C. In a pathway with a roughly 50% chance of peaking below 1.5°C, global emission reductions by 2050 should be around 80% from 1990 levels and global emissions need to peak within the next 5 years. The latter implies there is no flexibility in allowing delayed participation by some countries. This default 1.5°C pathway is illustrated by the green line in Figures 4 and 9–12.

Alternatively, one could gamble on a temporary overshoot above 1.5°C and a drop down to 1.5°C not too long after 2100. Obviously, this is more risky, since it depends on our current best estimate of the reversibility of the climate system's warming course. Some mechanisms might prevent this: a recent study suggested that crossing the threshold to large-scale disintegration of ocean-floor methane hydrates might initiate a structural release of methane large enough to prevent warming to drop below 2°C for multiple centuries, or even millennia⁸⁷, even if anthropogenic emissions were eliminated. Also, during the time period of warming-limit overshoot, important thresholds to tipping points as presented in Section 2 might be crossed. Some might be resilient to warming temporarily exceeding a threshold, but for others reversibility is questionable at best and losses in biodiversity, for example, are irretrievable on a human time scale. If one accepts these risks, one illustrative pathway would require global reductions by 2050 comparable to a 2°C pathway (50% by 2050). However, to compensate for the high pre-2050 emissions, a post-2050 global removal rate of CO₂ from the atmosphere is required on the very edge of what is currently seen as feasible in the literature regarding, for example, BECCS deployment and potential – and would have to be sustained for at least a century. Hence, such a pathway is not only risky from a climate-system point of view, but also regarding the feasibility and potential of CO₂ removal technologies.

5. Role of Europe in a 1.5°C pathway

5.1 Annex I v. non-Annex I

As explained in Section 4.3, global emissions must be reduced to at least 50% and probably, for a less risky pathway, to 80% below 1990 by 2050 for a 1.5°C limit in the long term. Although 2020 levels are important, mid-century levels are critical to achieving 1.5 or 2°C⁸⁸. For the two extreme ends of this 2050 global reduction range, we show in Tables 1 and 2 that Annex I emissions need to be reduced to 85–95% below 1990, assuming developed (Annex I) and developing (non-Annex I) countries reach equal per capita emissions by 2050, as a very simple measure of equity. Obviously, this indicator does not account for historical responsibility and other more sophisticated considerations of equity, which would in some cases imply negative emission allowances for developed countries⁸⁹. Some such more sophisticated considerations would also require some developing countries (such as currently ‘Newly Industrialised Countries’ and ‘Rapidly Industrialising Countries’^u) to take on large reductions below 1990 by 2050, while for example Least Developed Countries would be exempt⁹⁰.

5.2 Is the EU energy road map reduction by 2050 enough?

The European Commission’s energy road map 2050⁹¹ is the document that details scenarios to achieve the EU’s commitment to reducing greenhouse gas emissions to 80–95% below 1990 levels by 2050. However, as the accompanying documents⁹² specify, the scenarios achieve a reduction of 80% by 2050. As noted above, Annex I as a group needs to reduce to 85–95% below 1990 by 2050, so that the EU’s commitment is roughly consistent with a 1.5°C target, but the reductions achieved by the energy road map fall somewhat short. Given more sophisticated considerations of equity, the EU’s commitment will probably have to be more ambitious. This implies that the EU’s commitment itself, as well as a reduction consistent with 1.5°C would need to rely on continued carbon trading.

Table 1. A reduction of global emissions to 50% below 1990 by 2050 constrains both Annex I and non-Annex I emissions. Only if Annex I emissions were reduced to 85% below 1990 would per capita emissions of the two groups converge by 2050.

	2050	2050	2050	2050	2050
Annex I emissions reductions from 1990	60%	80%	85%	95%	100%
Global emissions reductions from 1990	50%	50%	50%	50%	50%
Non-Annex I emissions reductions from 1990	30%	0%	<i>increase of 7%</i>	<i>increase of 22%</i>	<i>increase of 29%</i>
Annex I emissions per capita tCO ₂ e/cap	5.5	2.8	2.1	0.7	0.0
Non-Annex I emissions per capita tCO ₂ e/cap	1.4	2.0	2.1	2.4	2.5

^u Including countries like Argentina, Brazil, China, India, Indonesia, Mexico, and South Africa⁹⁰.

Table 2. As Table 1, for a reduction of global emissions to 80% below 1990 by 2050 constraining both Annex I and non-Annex I emissions. Only if Annex I emissions were reduced to 95% below 1990 would per capita emissions of the two groups converge by 2050.

	2050	2050	2050	2050	2050
Annex I emissions reductions from 1990	60%	80%	85%	95%	100%
Global emissions reductions from 1990	80%	80%	80%	80%	80%
Non-Annex I emissions reductions from 1990	107%	78%	70%	56%	48%
Annex I emissions per capita tCO ₂ e/cap	5.5	2.8	2.1	0.7	0.0
Non-Annex I emissions per capita tCO ₂ e/cap	(0.1)	0.4	0.6	0.9	1.0

6. Conclusions

In this report, we showed that a long-term global goal facilitates international negotiations and inspires policy worldwide. An assessment of the adequacy of a long-term goal of 1.5 or 2°C critically depends on the level of impacts associated with such levels of warming.

The past century and in particular last few decades have seen signals of anthropogenic climate change emerging as diverse as rapid sea-ice thinning in the Arctic, extreme seasonal heat, extreme droughts in the Mediterranean, decline of coral reefs and negative effects on agricultural yields. A 1.5°C rise by 2100 would prevent some of the worst impacts, but still poses serious challenges worldwide, especially in the LDCs, SIDS and Africa. From 1.5 to 2°C warming, impacts are projected to worsen and tipping points would be approached. For a warming of 2°C, severe and widespread droughts would occur in the next 30–90 years over many densely populated areas, including regions like southern Europe, Australia and large parts of Africa and North and South America. Water- and heat-stress will negatively affect crop yields in regions that are already drought-prone today, putting pressure on food security. 10–15% of Sub-Saharan ecosystem species would be at risk of extinction and a projected decrease in precipitation over the Amazonian forests may result in substantial forest retreat here. Due to ocean acidification, coral reefs would become impeded in growth at a CO₂ concentration of 450 ppm, a level reached around 2050 on a 2°C pathway. Sea level would rise to 80 cm above 2000 by 2100, only 5 cm above 1.5°C projections, thus resulting in comparable impacts. However, long-term stabilisation at 2°C warming implies a continuous sea level rise for centuries, with levels to approach 3 m by 2300. The threshold for the Greenland ice sheet to irreversibly melt in the very long term is now estimated to be 1.6°C above preindustrial, compared to the IPCC AR4 estimate of 3.1°C.

Current emission trends and reduction pledges put the world on a trajectory towards a temperature increase of roughly 4°C by 2100. At such levels of warming, impacts are the most severe, and many may be beyond the limits of adaptation. The conditions of some of the most extraordinary heat waves experienced today will become the new norm and a completely new class of heat waves, with magnitudes never experienced before, will occur regularly. This will have severe but as yet un-quantified impacts on agricultural production and human health. The timing of warming is critical as the world population is expected to grow until the second half of the 21st century. Due to ocean acidification, corals around the world are likely to start dissolving above 550 ppm CO₂, a level reached by 2050 on a 4°C pathway. The Amazonian forest area is expected to contract to 25% of its original size and up to 30% of other tropical rainforests, in central Sumatra, Sulawesi, India and the Philippines, will be threatened by forest retreat. In Africa, 25%–42% of plant species could lose all suitable range by 2085. Climate change has the potential to catalyse rapid shifts in dynamic, out-of-equilibrium ecosystems, such as sudden forest loss or regional loss of agricultural productivity due to desertification. The ramifications of these shifts would be far-reaching, rang-

ing from extensive loss of biodiversity and diminished land cover, through to loss of ecosystem services. 4°C warming by 2100 would likely result in global temperatures stabilising at 6°C above the pre-industrial level over the next few centuries. No geological-historic analogue exists for the rapid warming projected under unmitigated climate change and it is fair to say that this will lead at least to widespread extinctions in ecosystems that are shown to have happened 55 million years ago during the Palaeocene-Eocene thermal maximum, which reached such a level of warming at a slower pace.

Warming can be limited to 1.5°C and below. Hypothetically, if all emissions were to be eliminated immediately, delays in the climate system and abrupt changes in atmospheric radiative forcing would let warming continue to rise to a best-guess level of 1.2°C above pre-industrial level, before embarking on a gradual decline. In the very long term, a warming limit of 1.5°C requires total greenhouse-gas concentrations plus the effects of aerosols to be below a level of 400 ppm CO₂eq. Since an immediate stop to all global emissions is obviously impossible, any mitigation pathway aiming at 1.5°C and below necessarily involves a peak-and-drop concentration profile. Energy-economic models are able to achieve the required low emission levels, also without expansion of nuclear energy, but this crucially depends on:

- Early and globally concerted mitigation, emission reductions implemented from 2013 onwards, and global emission peak by 2020.
- Rapid up-scaling and feasibility of large-scale bio-energy, and availability of forest sinks.
- High rates of energy efficiency improvements.
- Availability of carbon capture and storage technologies (CCS).

Constrained by real emissions until 2010 and energy-economic reduction potential until the 2020s, 1.5°C scenarios necessarily require net-negative CO₂ emissions in the second half of the 21st century. The later the emissions peak, the more CO₂ needs to be removed, starting around the 2050s. As biomass takes up carbon from the atmosphere through photosynthesis, extracting the CO₂ from biomass energy systems and storing it underground, it effectively produces useful forms of energy for society (electricity) while taking CO₂ out of the atmosphere – a negative emission. CO₂ removal also helps to limit ocean acidification. So-called “Short-Lived Climate Forcers” do not help in the long term, but might slow near-term warming. Non-CO₂ measures must never be interpreted as a means for “buying time” to allow delayed reductions in CO₂. The probability of exceeding 2°C warming in the 21st century more than doubles from 20% to 50%, if CO₂ reductions were delayed by just 10 years, with compensation in the near term by SLCF reductions. Given the slow removal of CO₂ from the atmosphere, its effect is set to linger for centuries.

Internationally pledged emission reductions for 2020 are inadequate, but options remain to close the “Emissions Gap”:

- 1) Increase the global share of renewables from an estimated 10% at present to 15% by 2020. This will help to close the Gap by 4 GtCO₂.
 - Increase further to a 20% share to close the Gap completely.

- 2) Intensify energy efficiency improvements, which play a key role.
- 3) Reduce subsidies for fossil fuels to decrease global emissions by 2 GtCO₂ by 2020.
 - Eliminating subsidies reduces fossil-fuel demand and emissions.
 - Fossil-fuel consumption subsidies worldwide amount to \$409 billion in 2010 and may grow to \$660 billion in 2020.
 - Global renewable-energy subsidies were only \$66 billion in 2010.
- 4) In the international negotiations context:
 - Implement the more ambitious “conditional” pledges. This would reduce the gap by 2 GtCO₂e
 - Minimise the use of lenient Land Use, Land Use Change and Forestry (LULUCF) credits and surplus emission credits. This would reduce the gap by around 3 GtCO₂e
 - Minimise the use of the surplus Assigned Amounts from the 2008-2012 Kyoto period. This would reduce the gap by 1.8 GtCO₂e
 - Avoid the double-counting of offsets and improving the additivity of CDM projects. This would reduce the gap by up to 1.5 GtCO₂e.
 - Reduce emissions from international shipping and aviation

Global emissions must be reduced to at least 50% and probably, for a less risky pathway, to 80% below 1990 by 2050 for a 1.5°C limit in the long term. Although 2020 levels are important, mid-century levels are critical to achieving 1.5 or 2°C. For the two extreme ends of the 50–80% global reduction range, developed-country emissions need to be reduced to 85–95% below 1990, assuming developed (Annex I) and developing (non-Annex I) countries reach equal per-capita emissions by 2050, as a very simple measure of equity. Although the EU’s commitment of 80–95% reductions below 1990 by 2050 is consistent with a 1.5°C pathway, published scenarios for the EU “energy road map” fall short at a maximum reduction of 80%. (see Appendix 1)

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Appendix 1:

Countries calling to limit warming to 1.5°C or 2°C above preindustrial

Contributed by Kirsten Macey

For many years the European Union has been calling for a limit to global warming to 2°C above pre-industrial levels. In 2008, AOSIS and LDCs called for this limit to stay well below 1.5°C above pre-industrial levels. Since then, many other Parties have been agreeing to this limit. Below is a summary of all the Parties who have called for a limit of 1.5°C or 2°C warming above pre-industrial levels.

Those countries calling for global temperature **to stay well below 1.5°C** comprise together a total of 107 countries, accounting for 7% of global energy and industry-related CO₂ emissions and about 26% of global population in 2005^v.

Those countries calling for global temperature **to stay below 2°C** comprise together a total of 45 countries, accounting for 81% of global energy and industry-related CO₂ and about 64% of global population in 2005¹.

These groups together comprise a total of 152 countries.

^v Sources:

Emissions - PRIMAP Baseline Reference: PRIMAP3 (2009) Potsdam Real-time Integrated Model for probabilistic Assessment of emissions Paths (PRIMAP), www.primap.org
Population - UN (2008) 'World Population Prospects: The 2008 Revision Population Database.', <http://esa.un.org/unpp>.

Group of countries supporting 1.5°C

1	Afghanistan	55	Malawi
2	Algeria	56	Maldives
3	Angola	57	Mali
4	Antigua and Barbuda	58	Marshall Islands
5	Bahamas	59	Mauritania
6	Bangladesh	60	Mauritius
7	Barbados	61	Micronesia, Federated States of
8	Belize	62	Morocco
9	Benin	63	Mozambique
10	Bhutan	64	Myanmar
11	Bolivia	65	Namibia
12	Botswana	66	Nauru
13	Burkina Faso	67	Nepal
14	Burundi	68	Nicaragua
15	Cambodia	69	Niger
16	Cameroon	70	Nigeria
17	Cape Verde	71	Niue
18	Central African Republic	72	Pakistan
19	Chad	73	Palau
20	Colombia	74	Panama
21	Comoros	75	Papua New Guinea
22	Congo, People's Republic	76	Peru
23	Cook Islands	77	Philippines
24	Costa Rica	78	Rwanda
25	Cote D'Ivoire	79	Samoa
26	Cuba	80	Sao Tome and Principe
27	Democratic Republic of the Congo	81	Senegal
28	Djibouti	82	Seychelles
29	Dominica	83	Sierra Leone
30	Dominican Republic	84	Singapore
31	El Salvador	85	Solomon Islands
32	Egypt	86	Somalia
33	Equatorial Guinea	87	South Africa
34	Eritrea	88	Sri Lanka
35	Ethiopia	89	St. Kitts and Nevis
36	Fiji	90	St. Lucia
37	Gabon	91	St. Vincent and the Grenadines
38	Gambia	92	Sudan
39	Ghana	93	Suriname
40	Grenada	94	Swaziland
41	Guatemala	95	Timor-Leste
42	Guinea	96	Togo
43	Guinea-Bissau	97	Tonga
44	Guyana	98	Trinidad and Tobago
45	Haiti	99	Tunisia
46	Honduras	100	Tuvalu
47	Jamaica	101	Uganda
48	Kenya	102	United Republic of Tanzania
49	Kiribati	103	Vanuatu
50	Lao People's Democratic Republic	104	Vietnam
51	Lesotho	105	Yemen
52	Liberia	106	Zambia
53	Libya	107	Zimbabwe
54	Madagascar		

Group of countries supporting 2°C

1	Argentina	24	Kazakhstan
2	Australia	25	Korea, Republic of
3	Austria	26	Latvia
4	Belgium	27	Lebanon
5	Brazil	28	Lithuania
6	Bulgaria	29	Luxembourg
7	Canada	30	Malta
8	China	31	Mexico
9	Cyprus	32	Netherlands
10	Czech Republic	33	New Zealand
11	Denmark	34	Norway
12	Estonia	35	Poland
13	Finland	36	Portugal
14	France	37	Romania
15	Germany	38	Russian Federation
16	Greece	39	Slovakia
17	Hungary	40	Slovenia
18	Iceland	41	Spain
19	India	42	Sweden
20	Indonesia	43	Switzerland
21	Ireland	44	United Kingdom
22	Italy	45	United States of America
23	Japan		

