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

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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 streamlining 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 the 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 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, already at levels as low as 1.5°C, compounded by the effects of global sea-level projected for this level of warming of 75 cm above 2000 by 2100. However, with temperatures dropping well below a 1.5°C increase, sea-level rise might stabilize 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 South-east Asia being especially at risk due to vulnerable low-lying and populated deltas.

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-Sahelian 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 CO_2 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 5cm above 1.5°C projections, thus resulting in comparable impacts. Long-term stabilization 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 down 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. 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 is predicted to increase three-fold (from 15.4% to 44.0%) by 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 CO_2, 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, is 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 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). East Asia, South-east Asia and South Asia are most affected with an expected 53-125 million people displaced. The Small islands 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 catalyze 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 ecosystems services. 4°C warming by 2100 would likely result in global temperatures stabilizing at 6°C above pre-industrial 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 CO_2eq. 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.

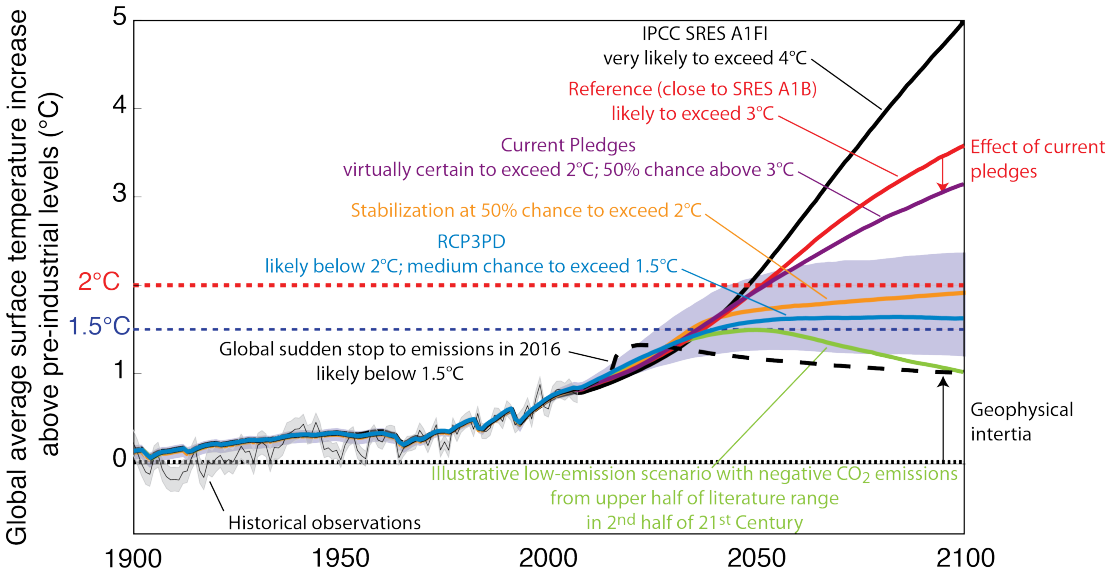
Socio-economic options for warming below 1.5°C are emerging from the scientific literature
Energy-economic models are able to achieve the required low emission levels, also without expansion of nuclear energy, but this crucially depends on:

- 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 CO_2 emissions in the 2nd half of the 21st century. The later the emissions peak, the more CO_2 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 CO_2 stays in the atmosphere for centuries, which is why emissions need to be reduced to near zero for stabilizing concentrations. However, this also means that concentrations decrease only slowly, unless CO_2 is taken out of the atmosphere by human interventions. As biomass takes up carbon from the atmosphere through photosynthesis, capturing the CO_2 from biomass energy systems and storing it underground, in effect produces useful forms of energy for society (electricity) while taking CO_2 out of the atmosphere – a negative emission. CO_2 removal also helps limiting acidification of the oceans.

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

Non-CO_2 measures must never be interpreted as a means for "buying time" to allow delayed reductions in CO_2. 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 CO_2 from the atmosphere, this effect is set to linger for centuries. Also, after a delay in CO_2 reductions, energy-related CO_2 reduction rates need to be almost double those in a "least-cost" low-emission pathway with early CO_2 measures. Without these higher reduction rates to "catch up", the CO_2 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 CO_2 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 pledges 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 $GtCO_2e$.

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 amounted 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.
   - Minimizing 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.
   - Minimizing 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 imply some developing countries (like currently 'Newly Industrialized Countries' and 'Rapidly Industrializing 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.

Contents

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 streamlining 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 discussion[1]:

"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 minimizes 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 organize 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° 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 to a global CO2 eq 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 pledged reductions are even more ambitions 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 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 stabilization 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 stabilize 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 to stay 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 to stabilize concentrations in the long term below present-day values (Figure 1).

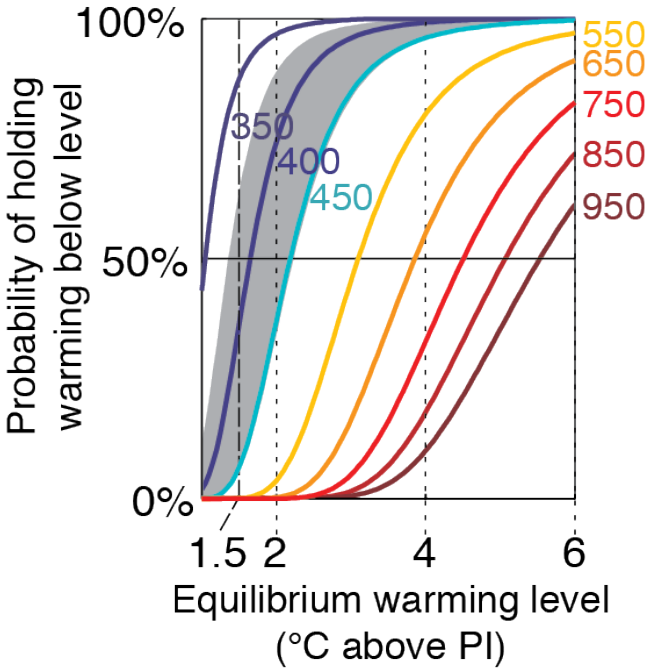


Figure 1 Probability to hold warming below temperature targets after the climate system reached equilibrium with a range of long-term fixed CO2-equivalent concentration levels (ppm CO2eq). The grey shaded area shows present-day CO_2-equivalent concentration without the cooling effect of aerosols (around 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-industrial [3]. Below 2.5°C, particularly strong climate change occur 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.

[a] RCP – Representative Concentration Pathway.

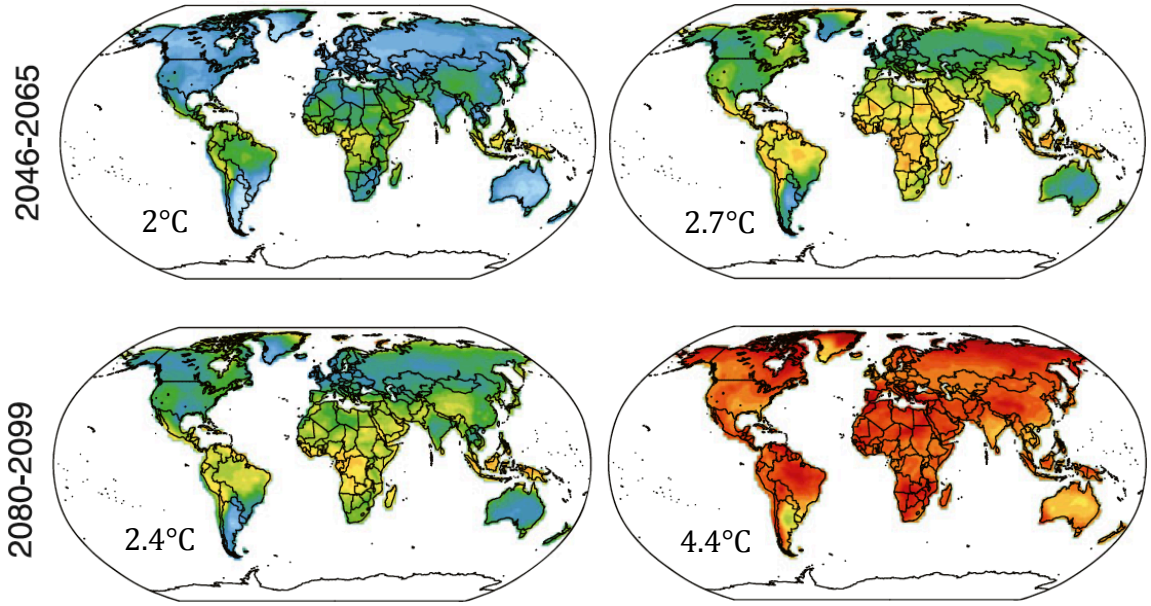


Figure 2 The relative aggregate climate change (an aggregate climate-change indicator including changes in temperatures, precipitation and extremes) between the 1986–2005 period and the 2046–2065 and 2080–2099 periods of RCP4.5 (left panels) and RCP8.5 (right panels). Source: Ref. [3].

Note that assessments of relatively high/low exposure to climate change in a certain region does 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 from actual extreme weather events[4]. 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 type of meteorological extremes there is now strong scientific evidence linking specific events or an increase in their number to the human influence on climate[5]. 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 forcing[8-10]. This implies that we can say with a high degree of confidence that recent high-impact heat waves, like the ones in Europe 2003, Russia 2010 and Texas 2011, are a consequence of the limited global warming to date[7].

[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.

Further, anthropogenic greenhouse gas and aerosol forcing are key attributable factors for the increased drying in the Eastern Mediterranean[11], accumulating in several extremely dry-years in Syria recently. As the vast majority of crops here are non-irrigated and therefore dependent on winter-time precipitation[12], the region is highly vulnerable to meteorological drought. In combination with water mismanagement, the meteorological drought in 2008 thus rapidly lead to water-stress with more than 40% of the cultivated land affected, strongly reducing wheat and barley production[12]. 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 volatility[16]. 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 trends[17]. 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 waves[21]. As an example, wheat production in Russia and Ukraine in 2010 was down by ~25% and ~20% respectively[18]. Since these countries are major global wheat exporters[22], grain prices increased strongly on the international market. The effects were magnified when the Russian government banned grain export to protect local consumers[21]. 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 bans[21].

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 bleaching[23]. The 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 scales[24]. Recent modeling 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 risk[25]. Tree dieback 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 decades[26]. 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 2030[29].

Recent science shows that coral reef ecosystems are likely to be extremely adversely affected by the combined effects of ocean acidification and warming, already at levels as low as 1.5°C[25]. Global sea-level is projected to rise to 75 cm above 2000 by 2100, but can be stabilized beyond 2100 below levels 1.5 m higher than today, with temperatures dropping well below a 1.5°C increase[30]. 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 warming[31]. Without adaptation such moderate sea level rise will increase the number of people flooded by storm surges more than five fold, with South and South-east Asia being especially at risk due to vulnerable low-lying and populated deltas[32].

2.1.3 2°C

For global warming up to roughly 2.5°C[33], the hydrological response is approximately linear with regions experiencing drier conditions under 1.5°C warming becoming even drier under warmer conditions[34]. Severe and widespread droughts would occur in the next 30–90 years over many densely populated areas[35], 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 2050[26]. Still, in a 2°C warmer world, water stress will be mostly dominated by population changes rather than climate change[34].

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 double[14]. Sub-Sahelian crop damages might exceed 7%, with a small chance of 27% damages[36]. 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 dates[16], 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 extinction[26] and a projected decrease in precipitation over the Amazonian forests may result in substantial forest retreat here[38]. At 2°C of warming roughly 25% of the original land extent of the humid tropical forest is at threat[38].

Sea-level would rise to 80 cm above 2000 by 2100, only 5cm above 1.5°C projections, thus resulting in comparable impacts. Long-term stabilization at 2°C warming however implies a continuous sea-level rise for centuries, with levels to approach 3 m by 2300[30]. The threshold for the Greenland ice sheet to irreversibly melt down is now estimated to be 1.6°C above preindustrial, compared to the IPCC AR4 estimate of 3.1°C[39].

2.1.4 4°C

Current emission trends and reduction pledges put the world in a trajectory towards a temperature increase of roughly 4°C by 2100. At such levels of warming impacts are most severe impacts, 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 world[42]. 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 peaks[34].

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 today[44]. Globally, drought disaster-affected areas in major crop sowing areas is predicted to increase three-fold (from 15.4% to 44.0%) in 2100[14]. 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 2080[43], 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 CO_2[49]. The Amazonian forest area is expected to contract to 25% of its original size[38] and up to 30% of other tropical rainforests, in central Sumatra, Sulawesi, India and the Philippines, is threatened by forest retreat[38]. In Africa, 25%–42% of plant species could lose all suitable range by 2085[50]. 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 loss[51]. 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 terrestrial plants carbon sink is actually expected to strengthen, due to the CO_2 fertilization effect, but it saturates above 3°C[52].

Climate change has the potential to catalyze rapid shifts in dynamic, out-of-equilibrium ecosystems, such as sudden forest loss or regional loss of agricultural productivity due to desertification[53]. The ramifications of these shifts would be far-reaching, ranging from extensive loss of biodiversity and diminished land cover, through to loss of ecosystems services[54]. Ecosystem degradation diminishes biodiversity, which decreases the overall stability of the ecosystem again. Recent work on competition and habitat suggests models generally underestimate the impact of climate change in biodiversity[55]. 4°C warming by 2100 would likely result in global temperatures stabilizing at 6°C above pre-industrial over the next few centuries[56]. 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 world[57]. 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 ago[58].

Sea-level rise (SLR) would exceed 1 m by 2100[30], with regionally possibly up to 20% higher values[41]. 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 are most affected with an expected 53-125 million people displaced. The Small islands 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 annually[61].

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[62]. New research shows mortality risk depends on tropical cyclone intensity, exposure, levels of poverty and governance[63].

2.2 Ocean acidification[c]

The previous section focused on impacts projected for different levels of global warming. However, the atmospheric CO_2 concentration has surpassed 380 ppm recently, which has not only led to climate change, but also to increased absorption of CO_2 by the oceans and an increase of the ocean's acidity, estimated at a reduction of 0.1 units of pH since pre-industrial[64]. 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 decades[65-67]. 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 a rising temperature of surface waters[68].

IPCC AR4 projections for SRES scenarios indicate a further increase of the ocean's acidity of 0.14 to 0.35 units of pH over the 21st Century[64], equivalent to an increase in acidity of 80-180% since pre-industrial. 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 events[69]. Recent research estimates that if atmospheric CO_2 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.

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

A scenario that is consistent with a 1.5°C warming limit may start to drop down to CO_2 concentration of 350 ppm by the end of this century. A recent assessment concluded a CO_2 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 quality[71].

2.3 Overview of impacts[d]

As mentioned in the introduction and clear from the previous sections, even limiting warming to 1.5°C will not prevent far-reaching impacts, particular 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, including through some identified 'tipping elements', like 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.

[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.

A SNAPSHOT OF A WARMING WORLD

As the agreements in Durban do not propose additional action before 2020 the risk of exceeding 2°C remains very high. Action to implement the Durban Agreements will need to be quick to increase emission mitigation, for having a chance of deviating projected warming from the current pathway leading to 3.5°C by 2100. A limit of 1.5°C will already lead to considerable impacts, and more with 2°C. But with temperature increases heading towards 3.5°C, the impacts reach a distinctly higher level of risk. The impact examples in this figure are illustrative and not comprehensive.

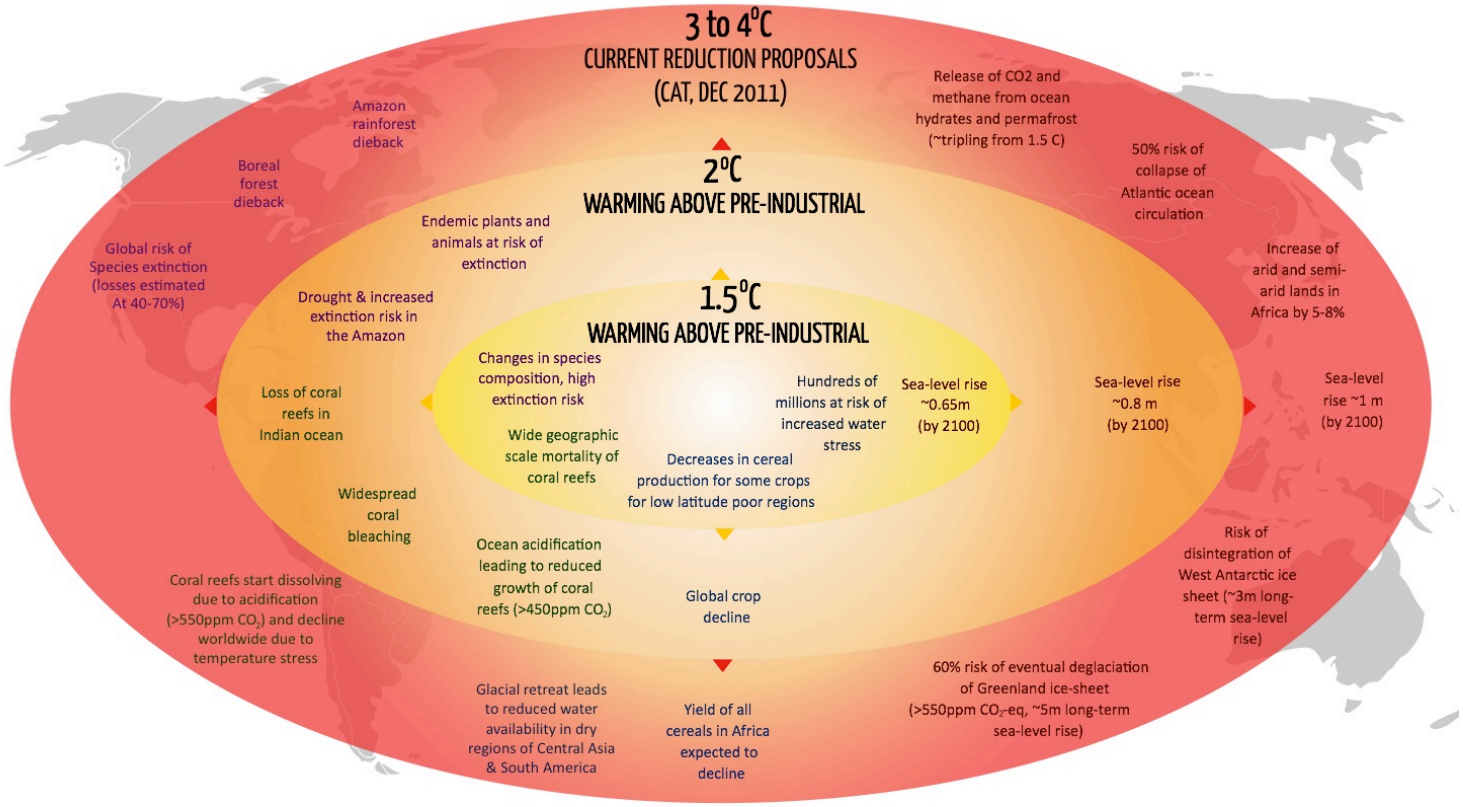


Figure 3. Overview of some of the impacts and tipping points at warming levels of 1.5 to 4 °C above pre-industrial temperature levels.

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).

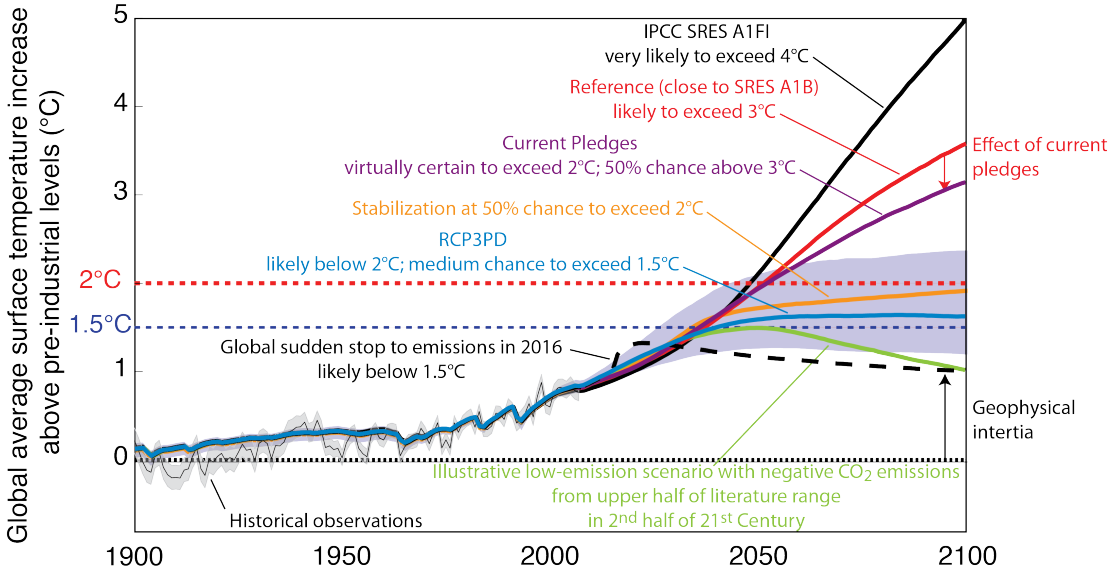


Figure 4. Median estimates (lines) from probabilistic temperature projections estimates for business-as-usual emission scenarios (SRES A1FI and Reference), as well as a wide range of mitigation scenarios holding warming below 2°C with a 50% chance or more[30,72,73]. The 15-85% uncertainty range is provided 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 stabilize, if global CO_2 emissions were reduced to near zero[74]. Delaying emission reductions results in higher cumulative emissions. Even if CO_2 emissions are brought down to zero after such a delay, the higher cumulative emissions lead to both concentrations and warming stabilizing 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 stabilize, at a level indicate in Figure 1, for example at more than 2°C for a concentration of 450 ppm CO_2eq. 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 CO_2eq concentration of all long-lived greenhouse gases amounted to about 455 ppm CO_2 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 CO_2eq. Any mitigation pathway aiming to achieve stabilization at 350 ppmv CO_2-equivalent

taking into account all Kyoto gases (CO_2, CH_4, N_2O and F-gases) hence necessarily involves a peak-and-drop concentration profile, dropping down from current concentrations to a value around 350 ppm CO_2eq.

3.1.1 Role of air pollutants[5]

Recent publications[75-77] have suggested that so-called Short-Lived Climate Forcers (SLCFs) might help to reduce near-term warming and stay below 2°C. The term SLFCs 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-CO_2 measures must never be interpreted as a means for "buying time" to allow delayed reductions in CO_2. 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 CO_2 and related sulphur reductions. After a delay to 2030, CO_2 emissions[6] 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 CO_2. 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 CO_2 measures has two important disadvantages, even if assuming a high present-day 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 CO_2 from the atmosphere, this effect is set to linger for centuries. Note that this delayed-CO_2 pathway still includes fully all of the incremental effects of reductions in HFCs, CH_4 and others of the original low- emission pathway and the higher warming by 2100 is solely the effect of the 10-year delay in CO_2 measures.

Secondly, energy-related CO_2 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 CO_2 measures. Without these higher reduction rates to "catch up", the CO_2 concentration and warming by 2100 will be even higher. From a multi-decadal perspective, delay scenarios have been shown to be riskier, requiring faster CO_2 reductions after a 10-year delay, and generally too expensive and/or technically infeasible[78,79].

[5] 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.

[6] SOx emissions would follow this downward path

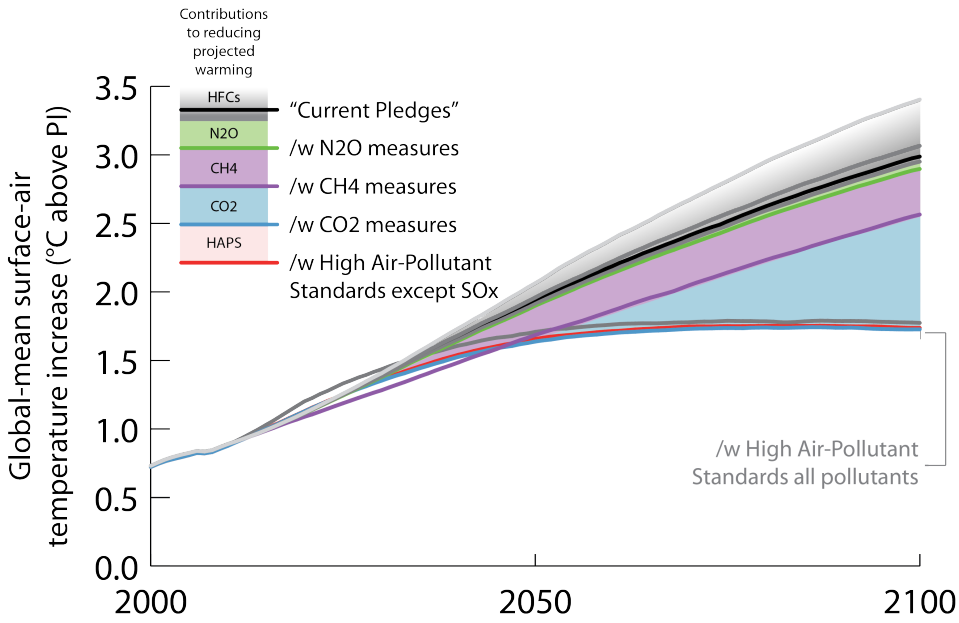


Figure 5. Incremental effects of emissions reductions of different greenhouse gases HFCs, N_2O, CH_4, CO_2, as well as air pollutants. The /wCO2 measures includes only those air pollution reductions consistent with energy system changes. This can be compared to low CO2 emissions with high air pollutant standards including SOx (grey) and without additional SOx 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 SOx emissions under a high air-pollutant standards scenario.

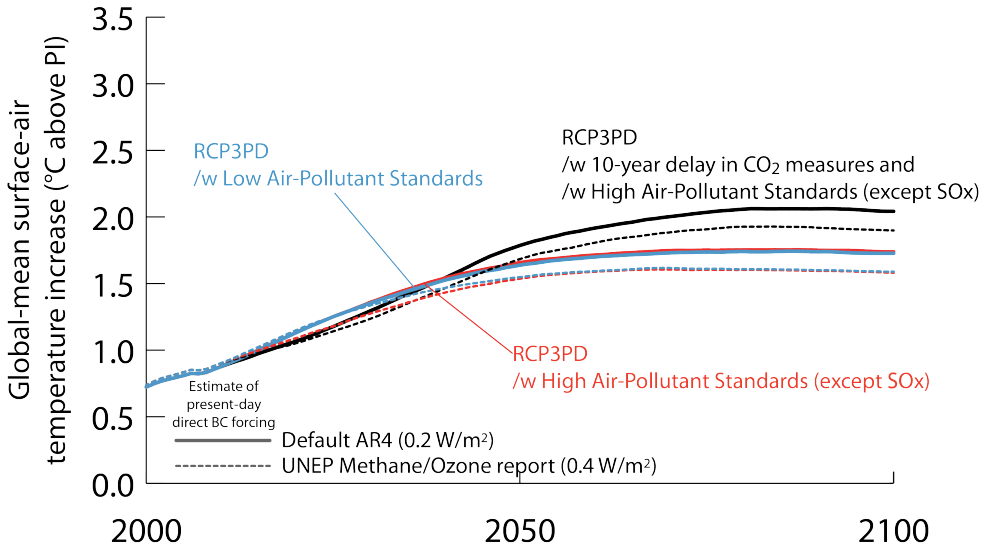


Figure 6 Global warming projections for low-carbon pathway RCP3PD (blue line) and a scenario where CO_2 reductions are delayed until 2030 but with large reductions in black carbon and related air pollutants, according to a shift from Low to High Air-Pollutant Standards, which exclude sulphur (black). In the delay case CO_2 and SOx emissions follow a scenario implied by current reduction pledges until 2030, where after 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 CO_2 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 AR4[80]. 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.

3.2 Energy-economic scenarios[7]

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 stabilization levels down to 400 ppm CO_2eq.

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 require net-negative CO_2 emissions in the 2nd half of the 21st century (Figure 7). The later the emissions peak, the more CO_2 needs to be removed starting around the 2050s (Figure 8).

Due to slowly responding carbon pools in the Earth system, a large part of emitted CO_2 stays in the atmosphere for centuries, which is why emissions need to be reduced to near zero for stabilizing concentrations, as mentioned above. However, this also means that concentrations decrease only slowly, unless CO_2 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)[8]. As biomass takes up carbon from the atmosphere through photosynthesis, extracting the CO_2 from biomass energy systems and storing it underground, in effect producing useful forms of energy for society (electricity) while taking CO_2 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 not more a form of geo-engineering than 'making the mess' by fossil-fuel consumption was in the first place. What is also important to realize is that CO_2 removal helps solve the issue of ocean acidification, which is not

[7] This section is adapted from Schaeffer, M. and F. Fallasch (2010) "Feasibility of low-emission pathways", Berlin, Germany, Climate Analytics, 11 June 2010.

[8] 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.

addressed by geo-engineering options that intervene in warming, for example by reducing the solar radiation input into the Earth system.

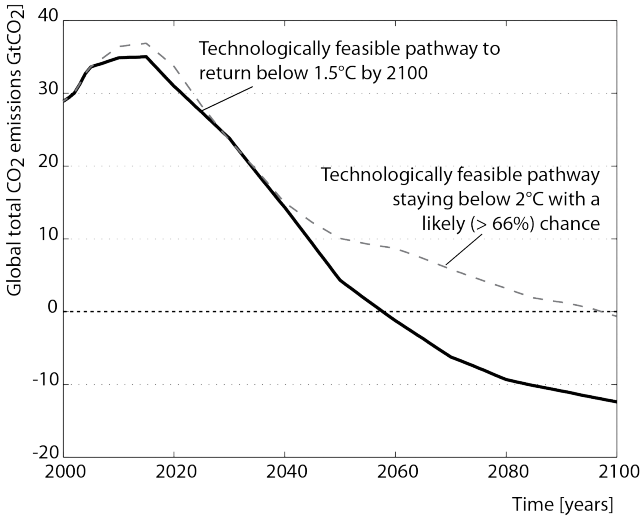


Figure 7 CO2 emissions in a 1.5°C scenarios overlap with a 2°C scenario until the 2030s, but require deeper reductions in the rest of the 21st century.

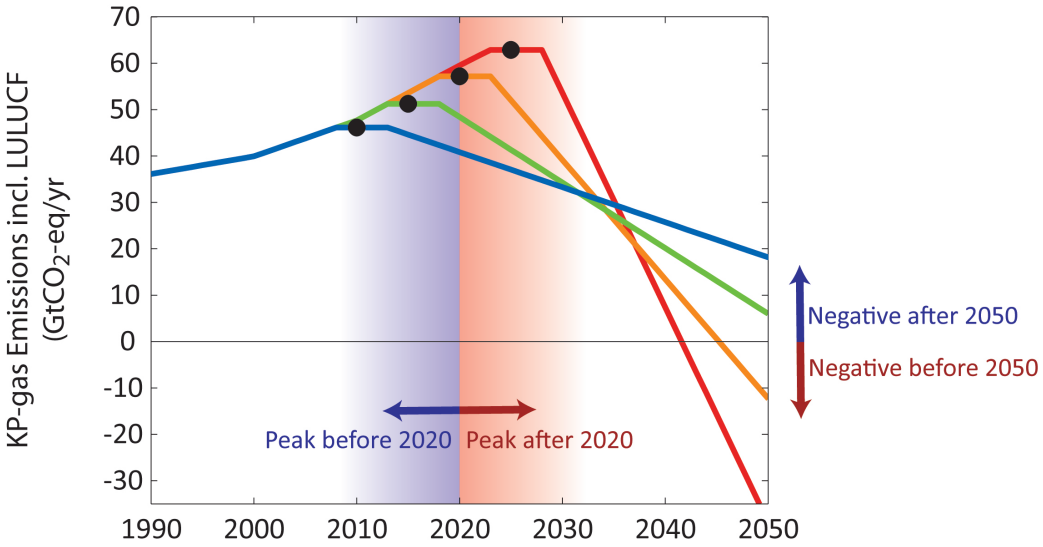


Figure 8 The effect of a delay in 2020 reductions, but keeping a fixed cumulative emissions in the period up to 2050 (hence a fixed probability of exceeding temperature targets) is to increase the required reduction rate up to 2050 and deepen the reductions needed by 2050. The blue line is comparable 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).

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-CO_2-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 CO_2 emissions over the full lifecycle of the process. In this system of Biomass Energy with Carbon Capture and Storage (BECCS), CO_2 sequestered during biomass growth before harvest is only partly re-released to the atmosphere, the other part being stored for geological time scales.

The extent of the ethical, political, ecological and legislative obstacles of the required large-scale overhaul of current land-use practices are under debate, but the technical potential may be sufficient to draw down CO_2 concentrations back to current levels before the end of the 21st century[9]. 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[10] of CO_2 by chemical processes is seen by some as an ultimate 'back-stop' technology to bring down CO_2 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 CO_2 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 program into the technology choices for limiting CO_2 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 in photovoltaics in many markets there is an expectation of grid parity within the next 5 to 10 years, which could revolutionize the market in this area. A scaled up research program 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[11]:

- The recent bio-fuels boom demonstrates two side 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 commercialization 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 CO_2 concentrations. If there are to be substantial negative emissions technologies introduced after the 2050s there would need to be substantial

[9] For an overview of the energy systems involved and their potentials in a strategy for drawing down the CO_2 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

[10] For an informal discussion, see Jones, N., Nature 458, 30 April, 2009, 1094-1097.

[11] 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

investment in research, development and demonstration and commercialization well before then. Hence there would need to be a scaled up investment in research and development of CCS technologies, and on environmentally sustainable ways of growing, producing and transporting biomass fuels. In order to develop the required scale there would need to be introduction into the energy system of technologies designed to achieve negative CO_2 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 CO_2 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 program 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 CO_2 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 a full decarbonisation by 2050. Various studies show that a transition to a completely renewable power infrastructure is possible within a relatively short time frame.[12] 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*"[13].

If the opportunity is used to transform the power sector the effects on CO_2 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 sector is possible to achieve in a very short time, but could also benefit climate by strengthening efforts in energy efficiency and renewable energy.[14]

[12] 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.

[13] Kyodo News, 29 March 2011. http://english.kyodonews.jp/news/2011/03/81780.html

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

The opportunity is even higher 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[15]. Nuclear power is also one of the few energy technologies to exhibit negative learning, in other words, increasing costs with time rather than decreases[16].

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-concistent scenario[17]. A wide inter-comparison of energy-economic models and scenarios[18] 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 modeling 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 policies[82].

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

[15] see e.g. Amory Lovins at http://www.huffingtonpost.com/amory-lovins/nuclear-power-fukushima-_b_837643.html
[16] Grubler, A. The costs of the French nuclear scale-up: A case of negative learning by doing. Energy Policy 38, 5174-5188 (2010)
[17] IEA. (2010). *Energy technology perspectives*. International Energy Agency (IEA), Paris, France, 18 pp.
[18] 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., Scrieciu, 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.

- 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.

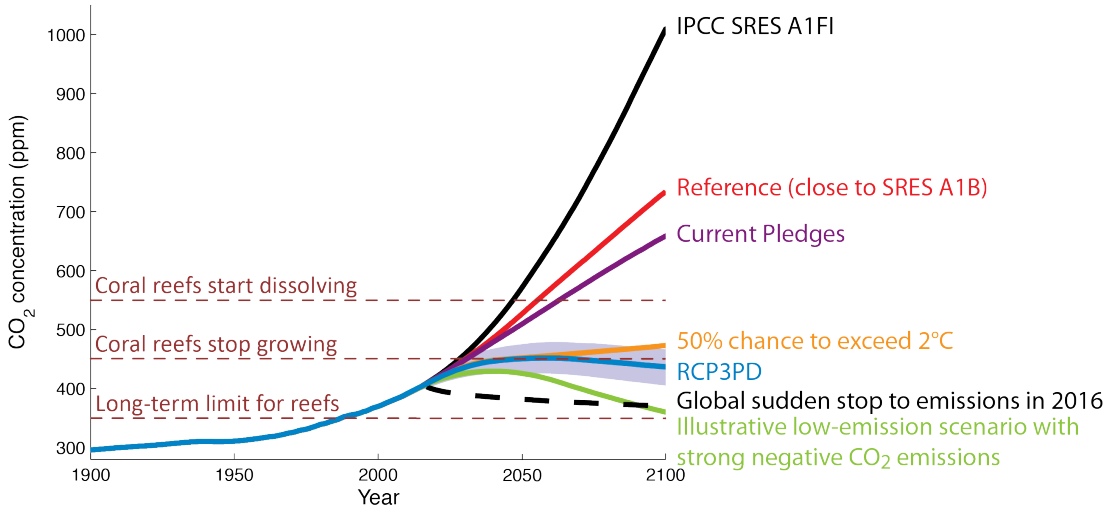


Figure 9. As Figure 4 for atmospheric CO2 concentration. Coral reef survival limits from Silverman et al. (2009) and Veron et al. (2009)[49,71].

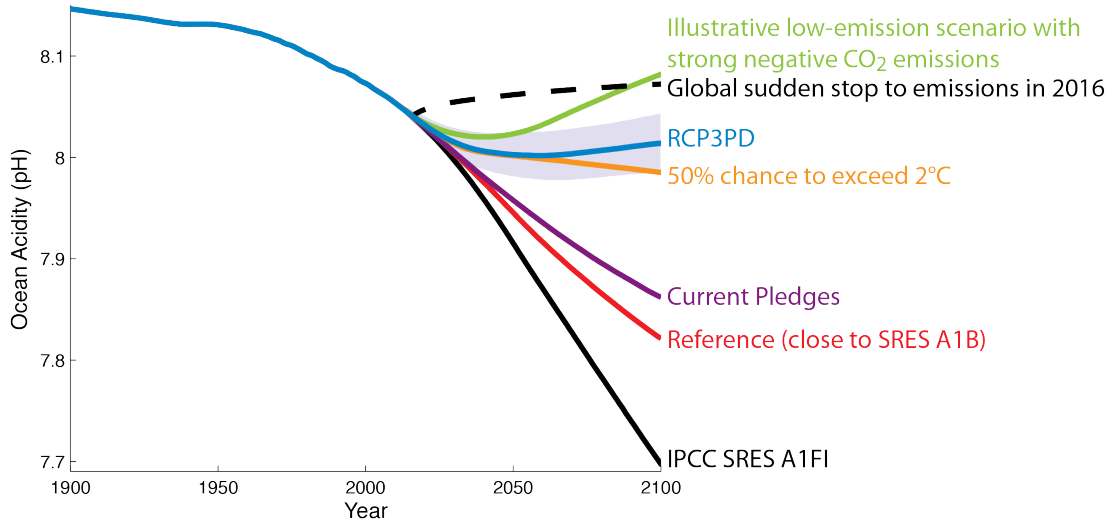


Figure 10. As Figure 4 for surface-ocean pH. Lower pH indicates more severe ocean acidification, which inhibits growth for calcifying organisms, including shellfish, calcareous phytoplankton and coral reefs. Method for estimating pH from Bernie et al. (2010)[83].

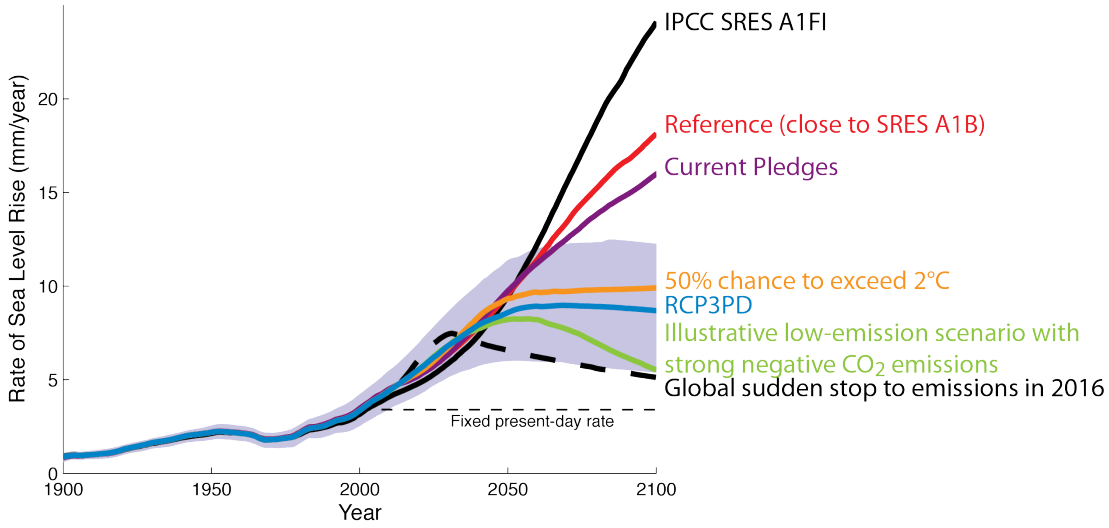


Figure 11. As Figure 4 for annual rate of global-mean sea-level rise. The indicative/fixed present-day rate of 3.3 mm.yr^{-1} is the satellite-based mean rate 1993–2007[84].

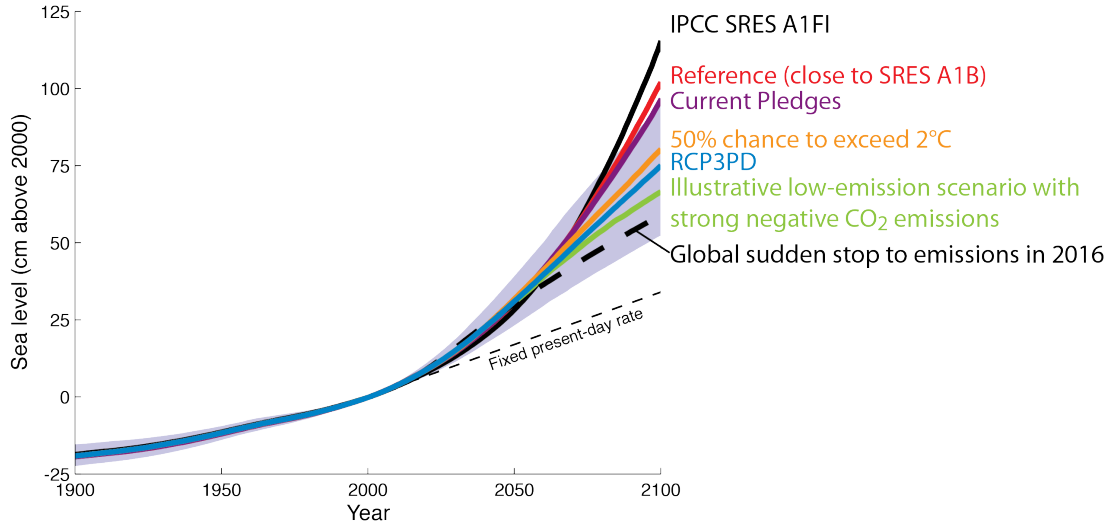


Figure 12. As Figure 4 for global-mean sea-level rise above 2000 levels. "Fixed present-day rate" illustrates sea-level rise of the 21st century if hypothetically the mean rate of change equals the rate observed by satellites over 1993-2007[84].

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[19]. 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.

[19] 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.

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 $GtCO_2e$. 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 chance 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[20] 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.
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 international negotiations context:
   - Implementing the more ambitious "conditional" pledges. This would reduce the gap by 2 GtCO2e.
   - Minimizing 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.
   - Minimizing 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.

[20] IEA (2011) "World Energy Outlook 2011", Paris, France

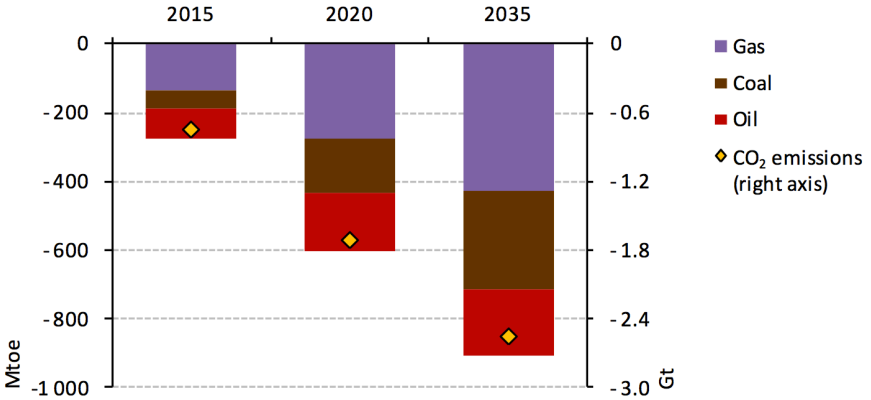


Figure 13 Impact of fossil-fuel consumption subsidy phase-out on global energy demand and CO2 emissions, 2012-2035. Source: "Joint report by IEA, OPEC, OECD and World Bank on fossil-fuel and other energy subsidies: An update of the G20 Pittsburgh and Toronto Commitments" Prepared for the G20 Meeting 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.

By contrast, reductions in Black Carbon and related air pollutants 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 CO_2 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 excluding comparably rapid action on SO_x emissions. However, such deep reductions in air pollutants still have large human health and other benefits.

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 CO_2. There is no lack of clarity about the energy-economic measures required to reduce CO_2, 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 CO_2 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[21] (see Figure 6). Without strong CO_2 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-CO_2 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 of the USA, to bring forward an argument for why the Emissions Gap is not really the key problem: *Rather than*

[21] 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.

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 $GtCO_2e$ 'Ambition Gap' is a much broader problem than the maximum estimated 1 $GtCO_2e$ '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 been ratified. Compared to the USA's current 2020 pledge of 17% below 2005, the global Emissions Gap would be narrowed by 1-2 $GtCO_2e$ 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 millennia[87], 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 temporary 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 excepts these risks, one illustrative pathway would require global reductions by 2050 comparable to a 2°C pathway (50% by 2050), but to compensate the high pre-2050 emissions a post-2050 global removal rate of CO_2 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 sustained for at least a century. Hence, such a pathway is not only risky from a climate-system point of view, but also regarding feasibility and potential of CO_2 removal technologies.

5 Role of Europe in a 1.5°C pathway

5.1 Annex-I vs 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°C[88]. 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 countries[89]. Some such more sophisticated considerations would also imply that some developing countries (like currently 'Newly Industrialized Countries' and 'Rapidly Industrializing Countries'[22]) take on large reductions below 1990 by 2050, while, for example, Least Developed Countries would be exempt[90].

5.2 Are the EU 2050 road map reductions enough?

The European Commission's low carbon and energy road map 2050[91] 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[92] specify, the scenario's 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%	*increase* of 7%	*increase* of 22%	*increase* of 29%
Annex I emissions per capita tCO2e/cap	5.5	2.8	2.1	0.7	0.0
Non Annex I emissions per capita tCO2e/cap	1.4	2.0	2.1	2.4	2.5

[22] Including countries like Argentina, Brazil, China, India, Indonesia, Mexico, and South Africa[90].

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 tCO2e/cap	5.5	2.8	2.1	0.7	0.0
Non Annex I emissions per capita tCO2e/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 the 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 negatively effected 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 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 CO_2 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 5cm above 1.5°C projections, thus resulting in comparable impacts. However, long-term stabilization 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 down 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 in a trajectory towards a temperature increase of roughly 4°C by 2100. At such levels of warming impacts are most severe impacts, much 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. This will have severe but as yet un-quantified impacts on agricultural

production and human health. 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 CO_2, 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, is threatened by forest retreat. In Africa, 25%–42% of plant species could lose all suitable range by 2085. Climate change has the potential to catalyze 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 ecosystems services. 4°C warming by 2100 would likely result in global temperatures stabilizing at 6°C above pre-industrial 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, 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 CO_2eq. 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 CO_2 emissions in the 2nd half of the 21st century. The later the emissions peak, the more CO_2 needs to be removed starting around the 2050s. As biomass takes up carbon from the atmosphere through photosynthesis, extracting the CO_2 from biomass energy systems and storing it underground, in effect produces useful forms of energy for society (electricity) while taking CO_2 out of the atmosphere – a negative emission. CO_2 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-CO_2 measures must never be interpreted as a means for "buying time" to allow delayed reductions in CO_2. The probability of exceeding 2°C warming in the 21st century more than doubles from 20% to 50%, if CO_2 reductions were delayed by just 10 years, with compensation in the near term by SLCF reductions. Given the slow removal of CO_2 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 international negotiations context:
    - Implementing the more ambitious “conditional” pledges. This would reduce the gap by 2 GtCO2e
    - Minimizing 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
    - Minimizing 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

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%.

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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 preindustrial. In 2008, AOSIS and LDCs called for this limit to stay well below 1.5°C above preindustrial 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 CO_2 emissions and about 26% of global population in 2005[23].

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 CO_2 and about 64% of global population in 2005[1].

These groups together comprise a total of 152 countries.

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

Group of countries supporting 2°C

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