Mitigating climate change through reductions in greenhouse gas emissions: the science and economics of future paths for global annual emissions

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Executive Summary

The 15th Conference of the Parties (COP15) to the United Nations Framework Convention on Climate Change (UNFCCC), due to take place in Copenhagen in December 2009, will aim to agree an international framework on climate change policy that will take effect after the first period of Kyoto Protocol expires in 2012, with binding targets for reductions in the emissions of carbon dioxide and other greenhouse gases. The overall objective of such reductions is, according to the UNFCCC, the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". However, there is no agreed overall target for stabilisation, and hence for the emissions reductions needed. As a result, several different targets have been proposed. During the second half of 2009, a political consensus began to develop that international policy on climate change mitigation should aim to limit the rise in global average temperature to no more than 2˚C above pre-industrial levels. References to this goal have appeared in successive drafts of the negotiating text ahead of COP15.

In order to inform the negotiations, the Grantham Research Institute on Climate Change and the Environment and the Centre for Climate Change Economics and Policy have produced this policy brief. It examines how much global emissions of greenhouse gases will have to fall from present levels to create a reasonable chance (i.e. a 50 per cent probability) of avoiding a rise in global average temperature of more than 2˚C above its pre-industrial levels, and explores the economics of achieving this target within the context of an international agreement on climate change policy.

Developments in the base of scientific evidence since the publication of the Stern Review (Stern, 2006) lead us to conclude that its proposal to set an upper limit of 550 parts per million (ppm) of carbon-dioxide-equivalent (CO_2e) for long-term stabilisation is too high. The risks associated with stabilisation at 550 ppm CO_2e look larger than previously thought. Using the same criteria, comparing the risks of inaction and the costs of mitigation action, the evidence points towards a long-term goal for international climate policy at the lower bound of the range of 450 – 550ppm CO_2e that was proposed by Stern (2006). This goal would aim to limit the chance of a global temperature change rising more than 2°C above pre-industrial levels to no more than 50 per cent, as well as limiting the chance of exceeding a rise of 4°C to much less than 5 per cent. This means that atmospheric concentrations of greenhouse gases should peak below about 500 ppm CO_2e within the next 40 years, and then decrease to no higher than 450 ppm CO_2e by around 2200; annual emissions would have to peak within the next 10 years.

No emissions path that is currently regarded as feasible offers a 100 per cent probability of avoiding a temperature rise of more than 2°C. Our analysis suggests that we may not be able to ensure more than a 50-50 chance of limiting warming to 2°C or less. The atmospheric concentration of long-lived greenhouse gases (which are the most important in terms of long-term warming) is estimated to be currently about 435 ppm CO_2e. This means that even if all emissions stopped today, there would still be a chance that global average temperature will rise by more than 2°C above pre-industrial levels.

From an assessment of the science and economics of emissions paths, we conclude that the goal of limiting to 50-50 the chance of global average temperature rising by more than 2°C above pre-industrial levels is demanding. But with well-designed policies applied consistently across countries, industries and greenhouse gases, the available evidence suggests that it is feasible. if a target can be hit, it need not cost more than a few percentage points of GDP. The benefits from limiting the risks posed by climate change are likely to be much greater, making the necessary investment very worthwhile. And there are likely to be important co-benefits from action from, for example, reduced local pollution and increased energy security.

Based on the science and economics, we conclude that, to limit the probability of exceeding warming of 2°C to 50 per cent, policy-makers should aim for annual global emissions to be between 40 and 48 Gt CO_2e by 2020. This is equivalent to limiting global annual emissions to levels in 2020 that would be between 8 and 30 per cent higher than 1990 levels. Although our scientific assessment suggests that permissible annual emissions could reach 54 Gt CO_2e in 2020 under some conditions, such a scenario would be subject to greater uncertainty and assumptions. In particular, such an emissions paths (which would result from 'delayed action' or low early ambitions for reductions) would require relatively high levels of aerosol emissions (which offset some warming) in the future, as well as an ability to reduce emissions to very low levels by 2050 (as low as 6 Gt CO_2e) and a reliance on unproven assumptions about the ability of the Earth system to recover quickly after 'overshooting' a target level for the atmospheric concentration of greenhouse gases. It would also require very strong and costly global emissions reductions after 2020. Therefore, an upper bound for annual emissions in 2020 of 48 Gt CO_2e would be more prudent. Further, our analysis suggests that it would now be politically unfeasible and probably prohibitively expensive to reduce annual global emissions to much less than 40 gigatonnes (Gt) of CO_2e by 2020 (i.e. close to 1990 levels). For example, reaching 40 Gt CO_2e would require halting emissions growth today and then reducing emissions at a rate of more than 3 per cent per year from, at the latest, 2014 onwards (by comparison, between 2000 and 2005, annual emissions grew at a rate of more than 2.5 per cent per year). Such a rate of reduction may be technically feasible, but would require very strong and immediate policy action, entailing high carbon prices and significant early scrapping of high-carbon plant and machinery.

We find that global annual emissions must peak by no later than 2020 to provide a reasonable chance of limiting warming to no more than 2°C above pre-industrial levels. The later the peak, the more rapidly emissions must be reduced subsequently. By 2050, global annual emissions would need to fall to no more than about 14-17 Gt CO_2e.

If action is delayed, with a less ambitious emissions target in 2020, reductions will have to be much more rapid up to 2050 and beyond to have a 50 per cent chance of avoiding warming of more than 2°C. A more ambitious path in the short term would reduce the economic costs of action. We conclude from the evidence that there are strong advantages in taking early action to reduce greenhouse gas emissions. First, as the costs of emissions reductions are likely to be lower in the early years compared with later, it makes sense to start out on an ambitious emissions path; the outlook for costs should then be re-assessed after a decade or two of experience in the light of technological developments. Second, delays in participation in a global regime for climate change policy are also likely to increase significantly the costs of achieving the target, without benefiting the 'late adopters', and may make the target impossible to reach. Finally, more rapid reductions later have a higher likelihood of running up against constraints on time and costs – for instance, of installing new capital and developing new technologies – especially if policy has not earlier set the appropriate incentives for businesses.

An ambitious long-term goal for climate change policies makes it imperative that a range of well-known market failures, particularly in relation to research, development and early deployment, are overcome. This could bring about a marked fall in emissions within a short period of time, as relevant market failures are tackled – correcting them does not necessarily require massive public spending or a lengthy period of investment or learning. Given the importance of innovation in driving economic growth in the long term, stimulating R&D in low-emissions technologies could also initiate a burst of entrepreneurial activity throughout the global economy, driving clean, green growth. There may also be periods of more rapid emission reductions in the future, particularly when low-carbon technologies become cost-competitive at scale in key sectors like power generation. But it is necessary to prepare the ground for such technological turning points.

Targets for annual emissions set at regular intervals and observations of carbon prices can be used to monitor and provide incentives to policy-makers to achieve the long-term climate goal that they adopt. It makes sense to choose targets for annual emissions that encourage early, co-ordinated and persistent action. An early peak in global emissions – before 2020 – is desirable, especially if policy-makers conclude that a discount rate lower than the market interest rate is appropriate.

Defining an envelope of paths for annual global emissions that all lead to a reasonable, 50 per cent, chance of avoiding a rise in global average temperature of more than 2°C above pre-industrial levels, and to a chance of less than 5 per cent of exceeding 4°C, is not a problem that can be solved exactly; the uncertainties involved are too great. Our approach therefore has been to provide estimates based on the best available evidence alongside information about the assumptions and uncertainties involved. While our conclusions about an emissions target for 2020 are broadly in line with other similar studies, there is considerable uncertainty around the appropriate targets for 2050. We estimate that the uncertainty range is of the order of ±5 to 10 Gt CO_2e in 2050 (for a given level of emissions in 2020).

Given the uncertainties in both the science and the economics, it is essential that any policy framework for climate change mitigation incorporates, from the outset, mechanisms to update the long-term goal, in a transparent fashion, in response to new developments in the science or economics, while holding policy-makers accountable for their actions. The Intergovernmental Panel on Climate Change could play a vital role in providing the scientific, economic and technical underpinning for revisions to the long-term goal.

1. Mitigating climate change through reductions in greenhouse gas emissions: background

Nicola Ranger, Alex Bowen and Bob Ward[1]

The 15th Conference of the Parties (COP15) to the United Nations Framework Convention on Climate Change (UNFCCC), due to take place in Copenhagen in December 2009, will aim to agree an international framework for climate change policy, including measures on both mitigation and adaptation. The UNFCCC was adopted in 1992 at the United Nations Conference on Environment and Development in Rio de Janeiro, Brazil (the Rio Earth Summit), and came into force on 21 March 1994. It has now been ratified by 192 countries. The aim of the Convention is stated in Article 2:

"The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner".

However, the UNFCCC does not specify at what level greenhouse gas concentrations should be stabilised through mitigation, but it does include a commitment in Article 4 by each developed country (listed in Annex I of the UNFCCC) to "adopt national policies and take corresponding measures on the mitigation of climate change, by limiting its anthropogenic emissions of greenhouse gases and protecting and enhancing its greenhouse gas sinks and reservoirs", with "the aim of returning individually or jointly to their 1990 levels these anthropogenic emissions of carbon dioxide and other greenhouse gases not controlled by the Montreal Protocol".

Objectives have been proposed that are alternatives to, although not necessarily incompatible with, those promoted by the UNFCCC. For instance, the 1939th meeting of the Council of the European Union in June 1996 concluded that "the Council believes that global average temperatures should not exceed 2 degrees [Celsius] above pre-industrial level and that therefore [atmospheric] concentration levels lower than 550 ppm [parts per million] CO_2 [carbon dioxide] should guide global limitation and reduction efforts".

The target of restricting a rise in global average temperature to no more than 2°C remains the primary mitigation objective of the European Union for international climate policy. For instance, the European Union and States of the African, Caribbean and Pacific Group issued a joint declaration on climate change and development in May 2009, which included: "taking note of the latest scientific research which indicates that achievement of the necessary global emissions trajectory to keep the 2 degrees Celsius objective within reach will require developing countries as a group, in particular the most advanced among them, to achieve a substantial and quantifiable deviation below the currently predicted emissions growth rate".

Stern (2006) noted that a target of avoiding a rise in global average temperature of more than 2°C has both strengths and weaknesses: "This goal allows policy-makers and the public to debate the level of tolerable impacts in relation to one simple index, but it does not provide a transparent link to the level of mitigation action that must be undertaken". Nonetheless, it has now been adopted by other countries. At their summit in L'Aquila in July 2009, the leaders of the Group of Eight (G8) countries (Canada, France, Germany, Italy, Japan, Russia, United States of America, United Kingdom) issued a communiqué that stated: "we recognise the broad scientific view that the increase in global average temperature above pre-industrial levels ought not to exceed 2°C". Similarly, the "Declaration of the Leaders" at the Major Economies Forum on Energy and Climate Change (including Australia, Brazil, Canada, China, the European Union, France, Germany, India, Indonesia, Italy, Japan, Korea, Mexico, Russia, South Africa, the United Kingdom, and the United States of America) stated: "We recognize the scientific view that the increase in global average temperature above pre-industrial levels ought not to exceed 2 degrees C".

This target has also been included within successive versions of the negotiating text for COP15, alongside alternative mitigation goals expressed in terms of other temperature thresholds, stabilisation of atmospheric concentrations of carbon dioxide and other greenhouse gases, and annual emissions of greenhouse gases by Parties to the UNFCCC.

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In order to inform policy discussions, the Grantham Research Institute on Climate Change and the Environment and the Centre for Climate Change Economics and Policy have produced this policy brief that examines by how much global emissions of greenhouse gases must be reduced to create a reasonable chance (i.e. 50 per cent probability) that global average temperature will not rise by more than 2˚C above pre-industrial level. In this Part, we consider the appropriate definition of a long-term goal for international climate policy, referring to the conclusions of the Stern Review (Stern, 2006) and more recent evidence. Part 2 of this policy brief examines the options, in terms of 'paths' for annual global emissions, which give a 'reasonable chance' (i.e. 50 per cent probability) of preventing global average temperature from rising more than 2°C above its pre-industrial levels. Part 3 explores the economic cost and feasibility constraints on these targets and the implications for international policy on climate change mitigation. These Parts should be considered together: a global emissions target must be informed by both science and economics.

1.1 The role of goals and targets in international policy on climate change mitigation

An overall goal for international policy on climate change mitigation must fulfil three criteria: effectiveness in reducing greenhouse gas emissions on the scale required; efficiency, in keeping costs down; and equity, in recognising differences in income, technologies and historical responsibility. Globally agreed goals and targets form the basis on which such policy frameworks can be built. They create a shared understanding of the scale of action required over time and facilitate international and national policies to achieve the required reductions in greenhouse gas emissions. Without such global goals, it is likely that national policies would not be inconsistent with each other, raising the costs of action and rendering inadequate the overall impact on reducing emissions. The greater the coordinated involvement of all emitters, the more likely are the actions and outcomes to be successful, cheaper and equitable.

International climate change policy requires both long-term goals and shorter-term targets. A long-term goal provides a valuable foundation for international collective action, delivering a shared understanding of the desired long-term objectives of climate change policy. This common appreciation of the scale of the challenge for both mitigation and adaptation and the direction of future policy action sets the constraints on short-term policy and can facilitate discussion of mutual responsibilities. Agreement on a process for setting credible long-term goals, derived in a transparent and coherent way, should reduce the uncertainty about future policy, allowing long-term planning, reduced costs of emissions abatement, less delay in the investment necessary to cut global emissions, and a coherent and sensible approach to adjusting policy instruments, such as emission caps, over time. Long-term goals should also help to reduce the volatility of carbon prices, a key tool in implementing climate change policy.

Shorter-term targets are essential to guide policy actions toward achieving a long-term goal. First, they should help to provide useful information to policy-makers about whether their policy instruments are working as expected and whether they need adjustment. Second, they should provide policy-makers with an incentive to meet the goal by ensuring that they can be held to account at regular intervals well before the date for achieving the long-term goal is reached. But short-term targets should also be formulated in such a way as to ensure that climate change policies are cost-effective. For example, if the short-term targets are expressed in terms of the driver of climate change, greenhouse gas emissions, they should make some allowance for the uncertainties about the pace of global economic growth, the extent and speed of technological innovation (particularly in the energy sector), and the scope for substituting goods and services, both in consumption and production, that do not entail intensive emissions of greenhouse gases[2].

What form should international policy goals take? The ultimate objective of halting human-induced climate change can be translated into a variety of possible long-term mitigation goals. Stern (2006) noted that the objective of the UNFCCC is defined in terms of the impacts of climate change that should be avoided, but "does not provide a quantitative guide to policy-makers on the action required". He pointed out that the objective of the UNFCCC can be classified as one of five types of possible long-term mitigation goals for international policy "to give guidance about the strength of measures necessary". Each type of goal has both strengths and weaknesses (see Table 1.1).

[2] The debate about the merits of annual emission quantity targets versus carbon price targets is relevant here; see, for example, the discussion in Chapter 14 of Stern (2006).

Table 1.1: Five types of mitigation goals (from Stern, 2006)

Type of mitigation goal	Advantages	Disadvantages
Maximum tolerable level of impacts (e.g. no more than a doubling of the current population under water stress)	• Linked directly to the consequences to avoid	• Scientific, economic and ethical difficulties in defining which impacts are important and what level of change can be tolerated • Uncertainties in linking avoidance of a specific impact to human action • Success not measurable until too late to take further action
Global mean warming (above a baseline)	• Can be linked to impacts (with a degree of uncertainty) • One quantifiable variable	• Uncertainties in linking goal with specific human actions • Lags in time between temperature changes and human influence, so difficult to measure success of policy actions in moving towards the goal
Concentration(s) of greenhouse gases (or radiative forcing)	• One quantifiable variable • Can be linked to human actions (with a degree of uncertainty) • Success in moving towards the goal is measurable quickly	• Uncertainties about the magnitude of the avoided impacts
Cumulative emissions of greenhouse gases (over a given time period)	• One quantifiable variable • Directly linked to human actions • Success in moving towards the goal is measurable quickly	• Uncertainties about the magnitude of the avoided impacts
Reduction in annual emissions by a specific date	• One quantifiable variable • Success in moving towards the goal is measurable quickly	• Uncertainties about the magnitude of the avoided impacts • Does not tackle the problem that impacts are a function of stocks not flows • May limit ‘what, where, when’ flexibility and so push up costs

Any operational goal should be closely related to the ultimate impact on well-being that policy seeks to avoid. But, if it is to guide decision-makers in adjusting policy sensibly over time, progress towards it must be easy to monitor. The goal must be clear, simple and specific. Potential temperature rise has been used as a single indicator of likely impacts of climate change, with more severe impacts from higher rises. What matters most in determining these impacts (particularly for the long-lived greenhouse gases such as carbon dioxide) is the cumulative emissions over time and the way that they influence atmospheric concentrations.

Stern (2006) argued that aiming to constrain the atmospheric concentrations of greenhouse gases below a certain threshold would provide an understandable and transparent guide for policy-makers. Concentrations of greenhouse gases in the atmosphere can be easily measured, and respond to emissions rapidly, enabling policy-makers and interested parties to monitor the effectiveness of action (particularly in light of the uncertainties in the carbon cycle) and allowing rapid feedback to nearer-term policy settings. Hence any policy goal based on impacts to be avoided, such as a temperature rise, should also be considered in terms of annual emissions and atmospheric concentrations of greenhouse gases.

1.2 Factors in setting long-term mitigation goals and targets

It is important to use science, economics and ethics together to inform policies aimed at slowing and eventually halting human-induced climate change. Science reveals the nature of the dangers and the foundations for technologies that can enable action to reduce greenhouse gas emissions. Economics offers a framework that can help policy-makers decide how much action to take and which policy instruments to use. Ethical considerations are vital in assessing the extent of action necessary and how any costs of action should be distributed. Only by putting together the science, economics and ethics can we develop a framework that provides robust guidance in setting rational and consistent international, and national, policies.

A number of approaches have been applied to the selection of long-term mitigation goals for international climate policy, based on various ethical perspectives. The balance of science and economics in these approaches ranges from largely science-driven (e.g. the precautionary principle) to largely economics-driven (e.g. formalised cost-benefit analysis). The advantages and disadvantages of such approaches are discussed in Watkiss *et al.* (2008).

The uncertainty about mapping from emissions to climate change impacts provides an argument for a more, rather than less, demanding goal, because of the size of the adverse climate change impacts in worse-case scenarios. For example, suppose that there is a probability distribution for the scale of physical impacts associated with a given increase in atmospheric concentrations of greenhouse gases. As one moves along the probability distribution, the consequences for global well-being become worse. But the consequences are also likely to get worse at an accelerating rate, for two reasons. First, the higher the temperature, the more rapidly adverse impacts are likely to increase. Second, the worse the outcome, the lower will be the incomes of people affected by them, so any monetary impact will have a bigger impact on well-being.

There is a second line of reasoning linking uncertainty with stronger action. There is an asymmetry due to the difficulty of reducing atmospheric concentrations of greenhouse gases. Increases are irreversible in the short to medium term (and very difficult even in the ultra-long term, given our current understanding[3]). If new information is collected that implies that climate change impacts are likely to be worse than we now think, we cannot easily go back to the concentration level that would have been desirable had we had the new information earlier. But if the improvement in knowledge implies that a less demanding goal is appropriate, it is easy to allow the concentration level to rise faster. In other words, there is an option value to choosing a lower goal than would be picked if no improvements in our understanding of the science and economics were anticipated. The 'option value' argument is not, however, clear-cut. There is also an option value associated with delaying investment in long-lived structures, plant and equipment for the abatement of greenhouse gas emissions. Investments in physical capital, like cumulative emissions, are largely irreversible, so there is an option value to deferring them. That argues for a higher level of annual emissions than otherwise desirable. Economists continue to debate which option value is larger. But individuals are likely to take into account the second – and only the second – option value, implying that it is up to policy-makers to take account of the first.

[3] It depends on the evolution of technologies such as biomass with carbon capture and storage, the ability to extend carbon sinks, such as tropical forests, and 'geo-engineering' solutions, such as reflecting more sunlight back into space, which have their own associated risks and ethical problems.

1.3 Previous advice about mitigation goals and targets

Stern (2006) suggested aiming for stabilisation of the atmospheric concentration of greenhouse gases within the range 450–550 parts per million (ppm) of carbon-dioxide-equivalent (CO_2e). The upper bound to this stabilisation range was strongly informed by a review of the scientific literature, which pointed towards two 'turning points' in the relationship between global temperature and impacts: a first turning point, where impacts are expected to become negative for many regions and sectors; and a second, where the risks of catastrophic and irreversible impacts (i.e. the limits to adaptability) become intolerable:

- it appeared that at a rise of about 2–3°C above pre-industrial levels, a significant proportion of species could exceed their adaptive capacity, leading to increased rates of extinction; crop yields could begin to decline sharply in many developing countries (and possibly some developed countries); some of the first major changes in natural systems, such as die-back of some tropical rainforests, might be seen; irreversible melting of the Greenland ice sheet and significant changes to the global carbon cycle (potentially accelerating the accumulation of greenhouse gases) could occur; and
- at around 4–5°C, the risk of major abrupt and irreversible changes in the climate system could increase markedly and global food production could begin to fall significantly.

There are large uncertainties in linking these types of temperature thresholds to long-term goals. Meinshausen (2006) demonstrated that a stabilisation level of 550 ppm CO_2e would give between a 45 and 95 per cent chance of keeping temperatures below 5°C (Box 1.1), with 8 out of 11 of the studies that were reviewed by the author indicating a probability of greater than 85 per cent. However, stabilisation at 550 ppm CO_2e would not avoid the lower 'turning point' of 2°C; according to the 'best guess' published in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2007); 550 ppm CO_2e would lead to eventual warming of just under 3°C, with an significant chance of considerably higher temperature increases. This was considered to be the maximum level of potentially deleterious outcomes that would be willingly borne by a person with relatively low aversion to risk, and/or a low valuation of impacts on ecosystems and poorer societies, and/or a high intergenerational discount rate. A more stringent goal would be required by a decision-maker with a higher aversion to risk, and/or a higher valuation of impacts on ecosystems and poorer societies, and/or lower intergenerational discounting.

The lower bound to the stabilisation range proposed by Stern (2006) was determined from an assessment of the feasibility and costs of mitigation. He concluded that the costs of mitigation consistent with a target of 500-550 ppm CO_2e were likely to be of the order of 1 per cent of global annual gross domestic product (GDP) by 2050, within a range of +/- 3 per cent. Studies of mitigation costs suggested that they did not rise very sharply with increased stringency of the long-term target until a point was reached when the required technological changes became infeasible. That point, Stern (2006) concluded, would very probably be reached if the target was as low as 450 ppm CO_2e, so he proposed that level as the lower bound of the range for the stabilisation goal. At 450 ppm CO_2e, the IPCC (2007) 'best-guess' would be an eventual warming of 2.1°C above the pre-industrial level in the 19th century.

Box 1.1: Linking global mean temperatures and stabilisation concentrations of atmospheric greenhouse gases

Table 1.2 shows the link between global mean temperatures and atmospheric concentrations of greenhouse gases at stabilisation (measured in CO_2e). This is a simplification and, therefore, can be used as a guide only. The second column (from the left) gives information on the likely (i.e. the 66–90 per cent range) and 'best guess' level of warming at different stabilisation concentrations of greenhouse gases, from IPCC (2007). The third and fourth columns give estimates of the implied probability of exceeding a 2°C or 4°C global temperature increase at stabilisation (above the pre-industrial concentration in the 19th century of 280 ppm CO_2e), based on Meinshausen (2006).

Stabilised greenhouse gas concentration (ppm CO_2e)	IPCC (2007) 'best guess' and 'likely' range of global mean temperature rise (°C) above pre-industrial levels	Implied probability of exceeding 2°C above pre-industrial levels (Meinshausen, 2006)	Implied probability of exceeding 4°C above pre-industrial levels (Meinshausen, 2006)
450	2.1 [1.4 – 3.1]	25% – 80%	<5% - 35%
500	2.5 [1.6 – 3.8]	50% – 95%	<5% - 45%
550	2.9 [1.9 – 4.4]	65% - >95%	5% – 55%
650	3.6 [2.4 – 5.5]	80% - >95%	15% – 65%
750	4.3 [2.8 – 6.4]	90% - >95%	30% – 80%

Table 1.2: An indicative relationship between stabilised concentrations of greenhouse gases and the global mean temperature at stabilisation (based on Meehl *et al*. (2007), Table 10.8), and the implied probability of exceeding warming of 2°C and 4°C above pre-industrial temperature at stabilisation (based on Meinshausen (2006), showing the range across all of the 11 climate sensitivity studies that were evaluated).

There are two major sources of uncertainty in the relationships shown in Table 1.2. The first is the uncertainty in the equilibrium climate sensitivity; that is, the level of warming we expect at stabilisation due to a doubling of carbon dioxide concentrations from pre-industrial levels. IPCC (2007) concluded, based on the available evidence, that there is a 66-90 per cent chance that the climate sensitivity lies in the range of 2.0 to 4.5°C, with a best-guess of 3°C. In Table 1.2, this conclusion translates directly into the estimates given in the second column. The third and fourth columns use a broader range of climate sensitivity estimates from 11 recent studies than IPCC (2007). The second uncertainty comes from the assumption made in converting the climate sensitivity estimates into stabilisation temperatures; that is, the climate system's feedbacks respond linearly to the forcing by greenhouse gases. This assumption is not proven and the limited data that are available suggest that we may be underestimating the stabilisation warming (and exceedance probabilities) for the higher stabilisation concentrations (i.e. above around 550 ppm CO_2e). This uncertainty is shown by the darker shading of the higher stabilisation concentrations. Full account must be taken of these two sources of uncertainties during decision-making.

Developments in the science of climate change since the publication of Stern (2006) lead us to a conclusion that the upper limit of 550 ppm CO_2e may not be stringent enough (Box 1.2). The risks associated with a greenhouse gas concentration of 550 ppm CO_2e appear to be higher than previously thought. For example, on the basis of new evidence, the risks of climate change for a warming of around 4°C would be similar to those expected by Stern (2006) to exist at around 5°C. In addition, the impacts associated with global temperatures close to and above 2°C would probably be more severe than previously thought. Using the same criteria as Stern (2006), comparing the risks of inaction to the costs of action, the evidence points towards a long-term goal for international climate policy at the lower bound of the Stern (2006) 450 - 550 ppm CO_2e range. Stabilisation at 450ppm CO_2e, for example, is estimated to give a probability of roughly 20 to 75 per cent of limiting warming to no more than 2°C above pre-industrial levels, and a 65 to >95 per cent chance of limiting warming to 4°C or less (with 8 out of the 11 studies suggesting odds of less than 10 per cent of exceeding 4°C) (Meinshausen, 2006). Our proposed long-term goal would aim to limit the chance of exceeding 2°C above pre-industrial levels to no more than 50 per cent, as well as limiting to much less than 5% the chance of global mean temperatures reaching 4°C above pre-industrial levels (i.e. as apposed to 5°C in Stern, 2006).

This conclusion is consistent with that reached by the UK Committee on Climate Change (2008): "to limit our central expectation of temperature rise by 2100 to as close as 2 degrees C [above pre-industrial levels] as possible, and reduce the risk of extremely dangerous climate change to very low levels (e.g. less than a 1% chance of a 4 degrees temperature rise)". This conclusion provides the basis for UK domestic emissions targets.

We also propose a new long-term goal, in terms of a peak level of atmospheric greenhouse gases. Stern (2006) proposed a long-term goal in terms of a stabilised level of greenhouse gases in the atmosphere, but this suffers from two main shortcomings. First, a stabilisation goal indicates little about the evolution of concentrations, and, therefore, of the change temperature and impacts over time. For example, if concentrations overshoot the target concentration significantly before stabilisation, the temperatures and impacts could be much greater than implied by Box 1.1. Second, a number of authors have commented that a more realistic path would be one through which concentrations peak and then decline over time. This means that the use of climate science in decision-making needs to move away from the simple framework illustrated in Box 1.1 towards a more dynamic framework of evolving emissions, concentrations, temperatures and impacts. The latter approach is taken in Part 2 of this policy brief. It is demonstrated that, given the current state of scientific knowledge, the temperature-based target (i.e. limiting to 50 per cent the probability of warming by more than 2°C, and limiting to less than 5 per cent the probability of warming by 4°C) is consistent with concentrations of greenhouse gases peaking at about 500 ppm CO_2e within the next 40 years and then declining to below 450 ppm CO_2e by around 2200 (based on a medium climate sensitivity of 3°C).

Box 1.2: New evidence on climate risks since Stern (2006)

There is **evidence that parts of the Earth's systems are responding more strongly to anthropogenic emissions and warming than has been previously observed or predicted by state-of-the-art models.** This suggests that we may be systematically under-estimating future impacts. For example:

- Since about 1990, global sea levels have been observed to be rising more rapidly than predicted by models (Rahmstorf *et al.*, 2007a). A potential cause of this discrepancy is an under-estimation of the sensitivity of the ice sheets on Greenland and Antarctica to warming; both ice sheets have been observed to be losing mass more rapidly than expected (e.g. Velicogna and Wahr, 2006). Ice sheet dynamics are not well represented in global climate models and this has led to the conclusion that sea level rise is likely to be larger than predicted by the models used for IPCC (2007) – e.g. Rahmstorf *et al.* (2007b), Smith *et al.* (2008).
- New evidence suggests that both terrestrial and marine biological systems are already being strongly influenced by recent warming (Parry *et al.*, 2007).
- There is stronger evidence that climate change is already impacting the frequency and intensity of many types of extreme events. Since the IPCC Third Assessment Report (2001), confidence has increased that extreme weather events will become more frequent, widespread and intense in a warmer world (Parry *et al.*, 2007).

New evidence has been published which explores a **broader range of potential impacts of climate change on economic and social systems, such as the effects on environmental migration and security, improving our understanding of possible vulnerabilities:**

- The severe effects of recent extreme weather events, such as flooding in China, heatwaves in Europe and tropical cyclones in the United States of America and Bangladesh, have highlighted higher levels of vulnerability to extremes than anticipated, each producing significant loss and property damage in both developed and developing countries (Smith *et al*., 2008). This, combined with the greater understanding of the effect of climate change on the frequency and intensity of extreme events, suggests that the impacts of these events could be more severe than previously thought.
- Recent studies indicate that the projected increase in frequency of many types of extreme events will also drive more negative effects on food production, beyond the impacts of mean climate change, creating the possibility of 'surprises', with impacts that are larger and occur earlier than predicted (Parry *et al.*, 2007). This is a particular risk for regions at lower latitudes.
- There is evidence that initial benefits from climate change will peak at a lower magnitude and earlier than was reported in IPCC (2001). IPCC (2007) concluded that it is very likely that all regions will experience either declines in net benefits or rises in net costs for increases in temperatures of more than about 3–4°C above pre-industrial levels (Parry *et al.*, 2007). It is projected that some countries at low latitudes and polar regions will experience net costs from even small increases in temperature.
- There is a growing body of evidence about the potential implications of climate change for migration and international security. The timing and magnitude of these effects remain uncertain, though the potential risks are clear. For example, the German Advisory Council on Global Change (2007) highlighted the potential for climate change to amplify mechanisms that lead to insecurity and conflict, in particular through its effects on water stress and food production in the poorest and most vulnerable regions, even at relatively low levels of warming (1-2°C). These socially-contingent impacts of climate change have not generally been included in studies that attempt to count the cost of climate change, but have the potential to be strongly non-linear drivers of damages.

Box 1.2: New evidence on climate risks since Stern (2006) *continued*

New evidence has emerged of potentially irreversible changes in the Earth's natural systems due to anthropogenic climate change. For example:

- There is stronger evidence about the possible impacts of climate change on ecosystems. IPCC (2007) concluded that the resilience of many ecosystems is likely to be exceeded by 2100 by an unprecedented combination of changes in climate, and their associated disturbances, and other anthropogenic drivers (land-use change, pollution and over-exploitation of resources) (Parry *et al*., 2007). Substantial changes in the structure and functioning of terrestrial and marine ecosystems were assessed to be very likely to occur with a global mean warming of around 2–3°C above pre-industrial levels, posing significant risks to many unique and threatened systems, including biodiversity hotspots.
- There is still much uncertainty around potential thresholds for 'large-scale tipping points' in the climate system that may have significant implications. Advances have been made in this field over the past few years. Some studies predict a rapid (and potentially irreversible) die-back of the Amazon rainforest at only a few degrees warming (Huntingford *et al*., 2008), with significant implications for both local and global climate. There is a medium confidence that at least partial deglaciation of the Greenland ice sheet, and possibly the West Antarctic ice sheet, would occur over a period of centuries for a global mean warming of around 2–5°C relative to pre-industrial levels (Lenton *et al*., 2008, Smith *et al*., 2008) . Based on an expert elicitation, Lenton *et al*. (2008) concluded that Arctic sea ice formation and the Greenland ice sheet are two systems with the highest sensitivity to warming, and the smallest uncertainty. Systems with intermediate sensitivity, but largest uncertainty, include the West Antarctic ice sheet, important natural patterns of variability like El Niño, the Indian summer monsoon and the west African monsoon system (both crucial drivers of extreme flooding and drought, particularly in the tropics), and the boreal and Amazonian rainforests. Lenton *et al*. (2008) suggested that changes to these systems constitute a greater risk of 'surprises'. The Atlantic thermohaline circulation is thought to have a low sensitivity, but intermediate uncertainty; IPCC (2007) concluded that an abrupt transition of the Atlantic thermohaline circulation is unlikely to occur before 2100.
- IPCC (2007) concluded that accelerated release of carbon from vulnerable stocks, especially peatlands, permafrost soils and soils of boreal and tropical forests, is virtually certain (Parry *et al*., 2007). Given continued unabated emissions of greenhouse gases, the terrestrial biosphere is likely to become a net carbon source by 2100, amplifying climate change (Parry *et al*., 2007).

[4] Lenton *et al*. (2008) suggested a slightly lower and narrow range of 1-2°C for melting of the Greenland ice sheet than that outlined here and in IPCC (2007) because of rapid recent loss of mass and observations of rapid reductions in Arctic sea ice (which amplifies warming over Greenland).

1.4 Translating a long-term goal into international targets

The previous section considered the benefits of setting a long-term mitigation goal for international climate policy in terms of limiting the chance of exceeding some target level of rise in global average temperature. To achieve this, the more urgent and immediate priority must be to constrain the level at which atmospheric concentrations peak. The amplitude of the peak and the time spent at the peak level are crucial determinants of the path of global mean temperatures and, therefore, of the scale and timing of impacts.

To allow concentrations to peak, global annual emissions must themselves stop growing and then decline to a level that is balanced by the natural rate of uptake of greenhouse gases by the Earth's systems. The immediate goal of climate change mitigation policy must be to bring this about. Taking into account historical responsibility, in the near term this will probably mean setting targets to ensure that reductions in emissions by developed countries more than compensate for the growth in emissions by developing countries. In the longer term, the majority of countries will need to reduce their emissions.

The scientific evidence shows that the timing of the peak in global emissions, as well as the rate of global emissions reductions following the peak, are crucial determinants of the level at which atmospheric concentrations peak and, therefore, of the scale of the impacts of climate change. The level at which concentrations peak is very sensitive to the date of the emissions peak.

1.5. Durability of a long-term mitigation goal

Given the uncertainties, it is essential that any policy framework for climate change mitigation incorporates, from the outset, mechanisms to update the long-term goal in a transparent fashion in response to new developments in science or economics. The mechanisms should be clear in advance to make it more difficult for policy-makers to undermine the long-term goal through short-term domestic actions (e.g. relaxation of pressure on individual emitters). As society learns more, the long-term goal may need to be made more ambitious if, for example, progress in the development of low-carbon technologies is better than anticipated or if the likely impacts of climate change are predicted to be worse than expected. Equally, unexpected difficulties in speeding up technological progress or a downward revision of expected impacts would warrant a less challenging goal. The Intergovernmental Panel on Climate Change (IPCC) could play a vital role in providing the scientific and technical underpinning for revisions to a long-term goal.

A long-term goal is a device to help structure and calibrate international climate change policy. But it is only a means to an end – halting human-induced climate change – and it is useful to keep that in mind. Action must not be delayed in order to more precisely determine the long-term policy goal for climate change mitigation. It is crucial to acknowledge now that strong and urgent action is necessary and to start taking steps in the right direction while the shared understanding of the extent of action needed in the long-term is still evolving. That is another reason why it is desirable to have mechanisms for reviewing and updating a long-term goal.

2. Mitigating climate change through reductions in greenhouse gas emissions: climate science constraints on annual global emissions targets for 2020 and 2050[5]

Nicola Ranger and Alex Bowen[6] Jason Lowe and Laila Gohar[7]

Summary

This section describes climate modelling that has been used to explore options for emissions target that give a 50 per cent chance of avoiding warming of more than 2°C above pre-industrial levels, as well as a probability of much less than 5 per cent of avoiding warming of more than 4°C. Defining an envelope of emissions paths that are consistent with a temperature-based goal is not a problem that can be solved exactly; the uncertainties involved are too great. However, at the same time, there is an urgent need to inform the policy debate. Our approach therefore has been to provide estimates based on the best available evidence alongside information about the assumptions and uncertainties involved.

No emissions path that is currently regarded as feasible offers a 100 per cent probability of avoiding a temperature rise of more than 2°C. Our analysis presented here and in Part 3 suggests that we may not be able to ensure more than a 50-50 chance of limiting warming to 2°C or less. The atmospheric concentration of long-lived greenhouse gases (which are the most important in terms of long-term warming) is estimated to be currently about 435 ppm CO_2e. This means that even if all emissions stopped today, there would still be a chance that global average temperature will rise by more than 2°C above pre-industrial levels.

Our simulations suggest that to have a probability of 50 per cent of limiting warming to 2°C or less, annual global emissions must peak and then fall to, at most, 54 Gt CO_2e by 2020[8]. However, this upper bound depends on a number of assumptions; in particular, it assumes high levels of future aerosol emissions and the ability to reduce global emissions to very low levels by 2050. If aerosol emissions are lower over the coming decades[9], global emissions would need to be reduced more strongly, to below around 48 Gt CO_2e by 2020. Part 3 concludes that reducing global annual emissions to much less than 40 Gt CO_2e by 2020 (i.e. close to 1990 levels) now appears to be politically infeasible and probably prohibitively expensive. This means that emissions paths should aim to pass through a window of between roughly 40 and 54 Gt CO_2e in 2020, or 40 and 48 Gt CO_2e under lower aerosol emissions. **We find that annual global emissions must peak by around 2020 to give a reasonable chance of limiting warming to no more than 2°C. The later the peak, the more rapidly emissions would have to be reduced subsequently.**

Those paths that have lower reductions in 2020 have bigger cuts subsequently to have the same chance of avoiding a rise of more than 2°C. Emissions in 2050 would need to be between about 6 and 17 Gt CO_2e in 2050, or 14 and 17 Gt CO_2e with an assumption of lower aerosol emissions. Our results define a 'reversed window' of possible paths[10] – those paths at the high end of the window in 2020 would need to be at the low end of the window in 2050. This means that if we delay action in the short term, aiming for less ambitious emissions reductions in 2020, we will need to reduce emissions at a much more rapid rate subsequently up to 2050.

There are considerable uncertainties in estimates of emissions reductions required by 2050 to meet a temperature-based target; we estimate that the uncertainty range is of the order of ±5 to 10 Gt CO_2e in 2050 (for a given emissions level in 2020). This uncertainty highlights the need to reassess targets regularly as new evidence emerges, and to select a target for 2020 that allows flexibility in emissions reductions in the period afterwards.

Potential emissions targets lying towards the upper half of the window in 2020 (i.e. up to 54 Gt CO_2e) are associated with higher climate risks than those in the lower half, and rely on unproven assumptions about our ability to recover after 'overshooting' a level of atmospheric greenhouse gases. Less ambitious targets for limiting emissions in 2020 lead to higher rates of warming and higher peak levels of greenhouse gas concentrations, both of which would create higher risks. **Considering the range of uncertainties and the balance of risk, we conclude that a target for 2020 that is as close to 40 Gt CO_2e as is economically and technically feasible is likely to be the best option from a risk management perspective.**

[5] The authors gratefully acknowledge helpful reviews of this Part of the policy brief by Brian Hoskins and Piers Forster.

[6] Grantham Research Institute on Climate Change and the Environment and the Centre for Climate Change Economics and Policy, London School of Economics and Political Science, London, UK.

[7] Met Office Hadley Centre, Exeter, UK. As part of the AVOID programme.

[8] The total level of emissions of all greenhouse gases is usually measured in terms of 'carbon-dioxide-equivalent' (CO_2e). This measure allows one to compare and aggregate emissions of different greenhouse gases by weighting them according to their different global warming potentials. The global warming potential represents the warming effect and lifetimes of different greenhouse gases relative to carbon dioxide. For example, methane has a 100-year global warming potential of around 25; this means that over 100 years, the warming effect of a tonne of methane will be 25 times that of one tonne of carbon dioxide.

[9] Aerosol emissions, overall, tend to cool the climate. These emissions have been reduced strongly over the past few decades because of health and environmental concerns. We have considered two possible future scenarios for aerosol emissions, both of which assume some reduction in aerosol emissions as a proportion of overall greenhouse gas emissions, but at different (though equally plausible) rates.

[10] This 'reversed window' concept holds for paths that eventually converge to the same annual emissions 'floor' (i.e. the stable level of long-term residual emissions), which we assume is roughly 4–6 Gt CO_2e in 2100. In our study, this floor is assumed to consist mainly of emissions of methane and nitrous oxide from food production.

2.1 Introduction

With the negotiations ahead of COP15 yet to reach agreement about long-term goals for climate change mitigation, there is an urgent need to understand the relationship between different targets for temperature rises, stabilisation concentrations of greenhouse gases, and annual emissions. This means laying out openly the risks and benefits associated with different options for targets, particularly in relation to global annual emissions. The assessment of the risks and benefits must take into account the science and economics of climate change. This Part of the policy brief focuses on the science of emissions targets, using only the most basic consideration of feasibility. The two subsequent parts of the policy brief review evidence about the relative economic costs and technological feasibility of different target options, and the implications for international policy on climate change mitigation in the context of a global agreement.

Building on the analyses of Part 1, we assess the options for mitigation targets framed around the goal of limiting global annual emissions to lie on a path that is consistent with a ‘reasonable chance’ of limiting global mean warming to no more than 2°C above pre-industrial levels (where a ‘reasonable chance’ is defined as 50 per cent), and a probability of much less than 5 per cent of warming exceeding 4°C: our ‘climate goal’. As discussed in Part 1, no emissions path currently regarded as feasible offers a 100 per cent probability of avoiding a rise of more than 2°C. Atmospheric concentrations of long-lived greenhouse gases (which are the most important in terms of long-term warming) are estimated to be currently about 435 ppm CO_2e. This means that even if all emissions stopped today, we would still have some chance of warming exceeding 2°C. Despite this, our climate goal is, to some extent, a subjective choice, since other probability thresholds could be selected. With a greater risk aversion, one may desire a lower probability of exceeding these temperature thresholds, which would require larger reductions in annual emissions than those described here.

Defining an envelope of emissions paths that are consistent with a temperature-based goal is not a problem that can be solved exactly; the uncertainties involved are too great. For example, the probabilities of warming exceeding 2°C themselves have associated uncertainties that depend on the modelling approach. To illustrate the scale of these uncertainties, Meinshausen *et al*. (2006) estimated that stabilisation of atmospheric concentrations of greenhouse gases at 450 ppm CO_2e would lead to a probability of between 26 and 78 per cent (mean of 54 per cent) of a rise in temperature of more than 2°C, based only on different assumptions about climate sensitivity distributions. However, at the same time, there is an urgent need to inform policy. Our approach, therefore, has been to provide estimates based on the best available evidence and modelling, alongside information about the assumptions and uncertainties involved. Also of critical importance to the assessment is information on how the risks associated with the science, and the rates of reductions in annual global emissions, vary between the different options for targets.

2.2 Paths for annual emissions that have a reasonable chance of avoiding a temperature rise of more than 2°C

2.2.1 Creating an ensemble of emissions paths

Our analysis aims to explore an envelope of possible options for mitigation targets in 2020 and 2050 that are consistent with our climate goal. This includes an exploration of the ‘model space’ that contains possible values for annual emissions which peak and decline along defined paths. The envelope is based on an ensemble of plausible emissions paths that each has a 50 per cent chance of limiting warming to no more than 2°C. Specifically, we define this as meaning that the path has a median estimated warming of 2.0°C or below between now and 2200 (this is the more precise meaning of our ‘climate goal’). Paths must also give less than a 5 per cent probability of exceeding 4°C in 2100 and 2200.

The first step in the analysis was to generate a large ensemble of around 100 emissions paths and then to filter this down to a smaller, representative set of 20 paths that are approximately consistent with our climate goal. These 20 paths were then analysed using a probabilistic climate model to provide estimates of their implications for global mean temperature, as well as other useful diagnostics, such as atmospheric concentrations of greenhouse gases. Importantly, our analyses incorporate two different scenarios for aerosol emissions. Aerosols are produced predominantly by burning fossil fuels and overall tend to cool the climate, offsetting a portion of the greenhouse gas warming (temporarily); temperature-based targets are, therefore, quite sensitive to aerosol assumptions. It is not clear how aerosol emissions will change in the future; because of their negative impacts on human health and ecosystems, most developed countries have reduced their aerosol emissions strongly over the past few decades, and similar measures are beginning to be implemented in the developing world. For this reason, we have considered a ‘lower’ and ‘upper’ scenario, both with emissions declining in relation to the use of fossil fuels over time, but at different rates.

Other important uncertainties are introduced through the modelling of the Earth system's response to emissions; in this study 'parameter' uncertainties in the model (such as climate sensitivity and carbon cycle feedbacks) are treated probabilistically using an approach consistent with that in the AVOID Programme[11]. Model 'structural' uncertainties, associated with 'between-model' differences are estimated through comparisons with other studies. In addition to these uncertainties is a structural uncertainty due to the fact that the models do not include all potentially relevant physical, biological and chemical processes (e.g. methane feedbacks); for this reason, the uncertainties analysed here must be considered lower bounds on the real uncertainty. Further details of the approach are given in Annex 1 and the supplementary materials (posted at http://www.lse.ac.uk/grantham).

Our analysis has not explored all potential emissions paths. For example, we assumed that emissions roughly follow the reference ('business as usual' or 'baseline') scenario[12] published by the International Energy Agency (IEA) up until the peak in global emissions (with some slow-down in growth a few years prior to the peak). This assumption constrains the 2020 and 2050 targets quite tightly. If future emissions increase more rapidly than the IEA reference scenario, or past emissions have been under-estimated (as suggested, for example, by Le Quéré *et al*., 2009)[13], then the targets would need to be tighter, and vice versa. The envelope has also taken account of considerations in relation to feasibility. An important constraint imposed on the lowest possible bound to the envelope was that global annual emissions did not peak before 2015. It was also assumed that emissions reductions ramp up gradually after the peak, in effect meaning that emissions along our idealised paths are not reduced at a rate faster than roughly 5 per cent per year during the first five years after the peak. The result of this assumption is that the lower bound to the envelope is around 40 Gt CO_2e in 2020. The highest possible bound to the envelope was determined by the baseline emissions scenario and is, therefore, 54 Gt CO_2e in 2020. Part 3 of this policy brief considers these boundaries in more detail and concludes that annual emissions in 2020 that lie outside this range are likely to be implausible in the context of the 2°C goal.

2.2.2 What can we learn from the full ensemble?

Figure 2.1 shows global annual emissions of greenhouse gases (in CO_2e[14]) between 1990 and 2050 for our reduced ensemble of 20 idealised paths. The colours of the paths and shaded regions indicate their median (i.e. the 50th percentile) estimated increase in global mean temperature in 2100 under the upper aerosol assumption (i.e. the more relaxed constraint). The orange and red regions incorporate paths that exceed warming of 2.0°C above pre-industrial levels in 2100, and the blue and green regions incorporate paths that stay at or below 2.0°C. We also note that for all except one of the emissions paths (path number 15), median temperatures in 2200 are lower than in 2100. We find that global mean temperatures are around 0.1°C warmer in the lower aerosol scenario. Only the paths lying in the green region limit median warming to 2°C under this scenario. Detailed information on emissions and climate outcomes for each path is given in Annex 2.

[11] AVOID is a multi-partner research programme led by the Met Office Hadley Centre (MOHC) and funded by the UK government. Part of the programme is focused on the analysis of emissions paths. These analyses will use the same climate assumptions as in this study, but different specifications of emissions paths and a broader range of assumptions about emissions baselines and emission floors. http://www.avoid.uk.net/.

[12] The reference scenario from the IEA World Energy Outlook 2008 gives suggests global emissions of greenhouse gases will be approximately 48 Gt CO_2e in 2010 and 55 Gt CO_2e in 2020 (IEA, 2008). The 2009 estimates are around 2 Gt CO_2e lower in 2020, mainly because of the effects of the global recession (IEA, 2009a, 2009b). This is roughly consistent with the baseline emissions in this study: 47 Gt CO_2e in 2010 and 54 Gt CO_2e in 2020. The IEA's reference scenario can be considered a 'business as usual' scenario from today; it includes policies enacted or adopted (though not necessarily fully implemented) to date, but not policies under consideration (e.g. no 'targets' that are not backed up by commensurate action).

[13] Historical emissions of greenhouse gases are uncertain. For example, IPCC (2007) concluded that there is an uncertainty of ±4 Gt CO_2 per year in land-use emissions alone during the 1990s. In this study, we assume historical emissions of 37 Gt CO_2e in 1990 and 41 Gt CO_2e in 2000. These lie well within the range of other current estimates. For example, the World Resources Institute CAIT (http://cait.wri.org/) assumes 39 Gt CO_2e in 1990 and 42 Gt CO_2e in 2000. Le Quéré *et al*. (2009) reported new estimates of carbon dioxide emissions up to 2008 from the Global Carbon Project. The estimates of fossil fuel emissions in 2008 used in this study are consistent with those in Le Quéré *et al*. (2009), but our estimates of land-use change emissions lie at the bottom end of their range. This means that our estimate of total carbon dioxide emissions is 3 Gt CO_2e lower than that of Le Quéré *et al*. (2009). They also suggested that emissions from fossil fuel consumption are growing more rapidly than assumed in this study or in the IEA's World Economic Outlook 2009 (IEA, 2009a), due mainly to rapid growth in the emerging economies. If the higher rates continue over the coming years, this would imply that bigger emissions cuts would be required by 2020 than we have suggested in this policy brief.

[14] Following the approach of Meinshausen *et al*. (2005), the equivalence is based on global warming potentials from the IPCC Second Assessment Report (IPCC, 2005).

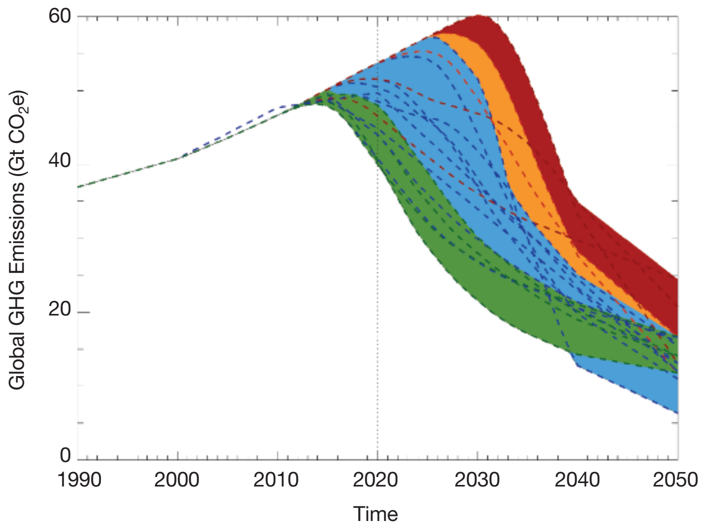

Figure 2.1: The ensemble of simulated emissions paths, with path colours and shaded regions indicating the median estimate of global temperature warming of the paths in 2100 in the upper aerosol scenario. The green region contains emissions paths that result in a warming of less than or equal to (≤) 1.9°C in 2100; the paths in the blue region result in a warming of ≤ 2.0°C; the paths in the orange region result in a warming of ≤ 2.1°C; and the paths in the red region result in a warming of ≤ 2.2°C. Note that median temperatures are around 0.1°C warmer with the lower aerosol assumption.

These findings suggest that the level of warming is more dependent on the level of annual global emissions in 2050 than in 2020, which is consistent with the conclusion of Meinshausen *et al*. (2009). However, in our case, this arises partly because we use only one 'business as usual' assumption and we did not explore sensitivities to emissions higher than 54 Gt CO_2e in 2020. We do see the strong link between the date of peak emissions and the median warming that was noted, for example, by Parry *et al*. (2009).

While this analysis has focused on paths that give a probability of at least 50 per cent of limiting warming to no more than 2.0°C, it is important to note that this also implies a chance of up to 50 per cent that any of these paths will lead to warming of greater than 2.0°C. But what is the range of possible temperature rises? We can express this by looking at the 10–90 per cent uncertainty range on temperature projections associated with the emissions paths (illustrated in Figure 2.4). In our simulations, we found that paths with a median warming of 2.0°C typically had a range of possible warming of between 1.5°C and 2.9°C (or roughly -25 per cent to +45 per cent of the median value)[15].

These uncertainties in the temperature projections have implications for both climate change mitigation and adaptation. In particular, the scale of the uncertainties highlights the challenges in assessing appropriate emissions targets objectively (particularly in the context of a temperature-based long-term goal) and the need to maintain flexibility and regularly reassess targets as new evidence emerges.

2.2.3 The envelope for a '50-50 chance' of 2°C warming

Figure 2.2 focuses on the envelope of those emissions paths with a probability of 50 per cent of limiting warming to no more than 2°C. These paths all have a median predicted warming of between 1.8 and 2.0°C (under the upper aerosol assumption). A key conclusion from this Figure is that the extent of flexibility in global emissions in 2020 to meet the 2°C goal is strongly dependent on assumptions about future aerosol emissions; only those paths in the darker blue envelope achieve the goal for both our upper and lower aerosol scenarios. We estimate that all of the 2°C paths considered have a probability of no more than 10 per cent of warming by more than 3°C, and less than 5 per cent probability of rising more than 4°C under both the upper and lower aerosol scenarios.

The wider envelope (in light blue, showing paths that achieve the 2°C goal under the upper aerosol scenario), has a window of between 40 and 54 Gt CO_2e in 2020. Note that this window is actually the full range of 2020 emissions explored in this study. The black lines show the two paths that pass through, respectively, the highest and lowest values of annual emissions in 2020; these cross at around 2035, and by 2050 have switched their relative positions within the envelope. This demonstrates that a lower level of emissions reductions in 2020 must be accompanied by stronger cuts subsequently to achieve the same goal. In the context of this envelope, this can be thought of as a 'reverse window' for annual emissions in 2050, which we estimate to lie between around 6 and 17 Gt CO_2e.

With the lower aerosol assumption, the windows are narrower; our findings suggest that in 2020 emissions would need to pass through a window of between about 40 and 48 Gt CO_2e, and in 2050, a 'reverse window' of about 14 to 17 Gt CO_2e.

[15] This uncertainty range is the 10th–90th percentile range from the model and is driven by model parameter uncertainty alone. From IPCC (2007), we estimate a model structural (i.e. between-model) uncertainty across the current range of models that would extend this range by a few tenths of a degree (Annex 2.A). However, this is still likely to be a lower bound estimate for the true uncertainty; for example, it does not take into account systematic biases that are known to exist across all climate models, such as some missing and potentially important process that could affect temperatures. Even so, we found that the uncertainty in the projection is actually larger than the median temperature difference between our warmest and coolest paths.

It should be noted that these windows are for guidance only; it is impossible to say for example that 53.8 Gt CO_2e should be considered acceptable, but 54.6 Gt CO_2e should not. The windows should be interpreted as the range roughly within which we should aim to keep annual emissions to have a 50-50 chance of meeting the 2°C goal. To have a probability of more than 50 per cent of limiting warming to no more than 2°C would require bigger cuts in annual emissions. The most important factor in determining temperature, and therefore impacts, is the evolution of greenhouse gas concentrations in the atmosphere; these are constrained by the path of emissions. Each of the emissions paths in Figure 2.2 mean that atmospheric concentrations of greenhouse gases would peak at around 500 ppm CO_2e within the next 40 years, before declining to about 450 ppm CO_2e or below by around 2200.

A strong finding of this study, which is consistent with those of others (e.g. Meinshausen *et al*., 2009; den Elzen *et al*., 2007), is that with a lower level of emissions reductions in 2020 would need to be accompanied by rapid reductions subsequently to achieve the same long-term goal (be it a temperature-based goal or concentration-based goal). This finding is clearly demonstrated in Figure 2.3. It also suggests, for example, that if one assumed that emissions could not feasibly be reduced at a rate faster than 5 per cent per year between 2020 and 2050, then one could conclude that global annual emissions would need to be kept below around 52 Gt CO_2e in 2020. Similarly, with a limit of 4 per cent per year, annual emissions in 2020 would need to be kept below around 49 Gt CO_2e. Part 3 explores in more detail these and other technological and economic constraints.

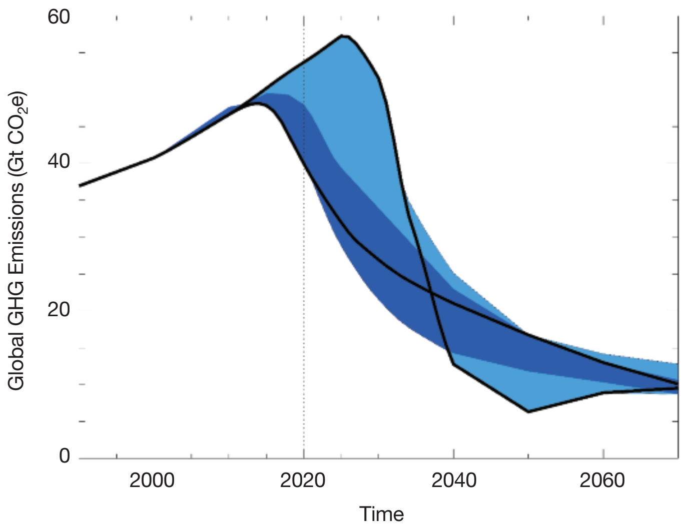

Figure 2.2: The envelope of simulated emissions paths resulting in median warming in 2100 of ≤2°C above pre-industrial temperatures. To have a lower median warming (or a higher chance of meeting the 2°C goal) emissions would need to be cut more strongly than represented by this envelope. The envelope based on the 'upper' (more relaxed) aerosol scenario is shaded in light blue. The envelope based on the 'lower' aerosol scenario occurs in dark blue. The two paths shown in black are those that form the top and bottom edges of envelope in 2020; note that they cross at around 2030, as paths with less ambitious reductions in 2020 will require stronger cuts in emissions afterwards.

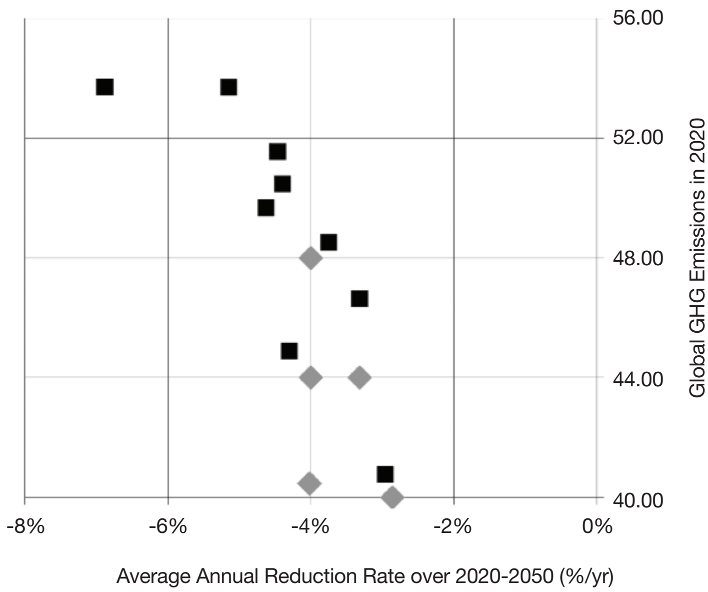

Figure 2.3: The relationship between global annual emissions of greenhouse gases in 2020 and the average annual rate of emissions reductions between 2020 and 2050, for emissions paths with a median temperature limited to 2°C above pre-industrial levels in 2100, for either the upper aerosol scenario (squares) or lower aerosol scenario (diamonds).

The 'reverse window' defined in this study also suggests that a target located at the higher end in 2020 will require a target at the lower end in 2050. In other studies, this result is not so strong, because they assume more flexibility in emissions after 2050, while here all paths reduce to a 'hard' floor of about 4–6 Gt CO_2e by 2100. This is discussed further below.

There is a clear relationship between the date of the peak in global annual emissions and the median level of warming, which is seen clearly in Figure 2.1. Here, emissions paths peaking beyond 2025 are associated with a median warming of greater than 2°C. Also, the later the peak in emissions, the more rapidly emissions must be reduced following the peak; for example, along a path that peaks in 2025, emissions must be reduced at 7 per cent per year over the period between 2020 and 2050 (or 8.5 per cent per year between the peak in 2025 and 2050) to produce a median warming that meets our climate goal, whereas the path that peaks in 2020 would require emissions reductions of, at most, 4.5 per cent per year to reach the same goal. The feasibility of such options is considered in Part 3. In the lower aerosol scenario, there is reduced flexibility; our findings suggest that global emissions would need to peak by around 2020 and then begin to fall rapidly[16].

Most of the paths converge towards the end of the century, reaching a stabilised 'floor' of around 4-6 Gt CO_2e. In this analysis, the floor level results mainly from emissions of methane and nitrous oxide from agriculture, with the assumption that any residual carbon dioxide emissions are approximately balanced by increased uptake through land-use change and the forestry sector (e.g. afforestation and reforestation programmes). The floor levels required appear quite low if we consider that emissions from agriculture alone in 2000 were around 5 Gt CO_2e and the global population in 2100 is likely to be at least 50 per cent larger than today (Stern, 2006). The feasibility of these floor levels is considered in Part 3. The analysis here suggests that if it is impossible to attain such low levels of emissions in the long term then it may be impossible to achieve the 2°C goal. Importantly, paths with a lower level of ambition in 2020 tend to require lower floor levels of emissions that must be attained earlier; this has implications for the feasibility of those paths and is considered in Part 3.

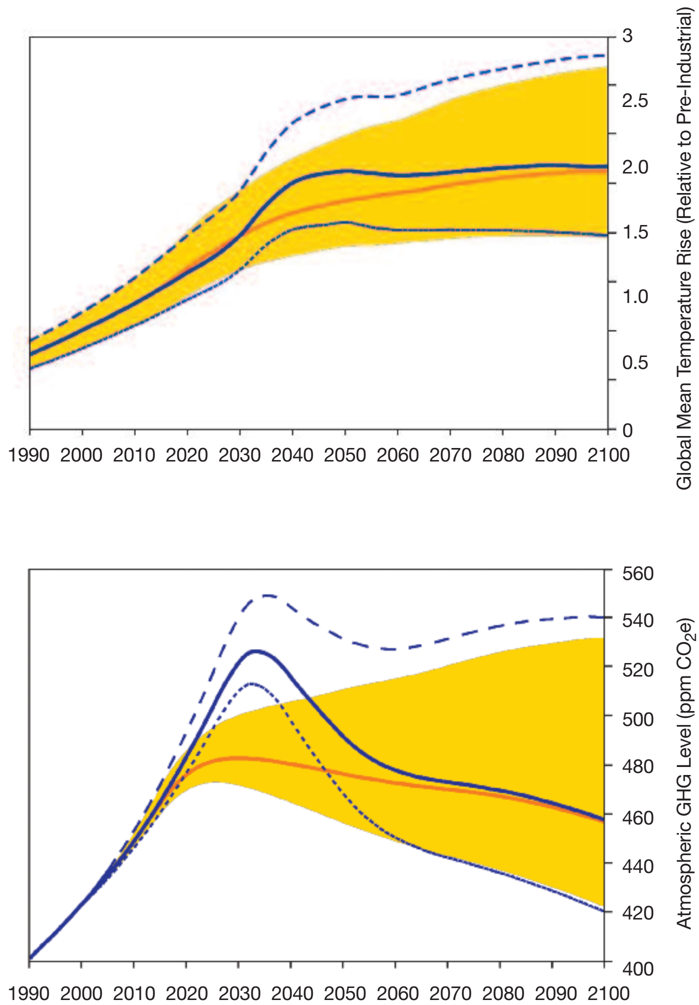

Figure 2.4: A comparison of the 10th, 50th and 90th percentile of (left) the estimated global mean warming and (right) the estimated level of Kyoto greenhouse gases, for the highest (in blue) and lowest (in orange) emissions path (respectively, paths 18 and 3) with an estimated median warming of 2°C in 2100 (higher aerosols). The solid lines are the median estimates. The 10th-90th percentile range of the lowest emissions path is bounded by the yellow shaded area, while for the highest path this range is bounded by the blue dashed lines.

[16] We note that these findings depend on the baseline emissions. If the baseline was higher (i.e. emissions grew more strongly than the IEA reference scenario prior to 2020), then for similar post-peak reduction rates, the global emissions peak would need to be earlier to achieve the same goal. It is not clear whether the opposite would hold for a lower baseline; that is, if annual emissions are reduced strongly earlier, and in 2020 are much lower than 54 Gt CO_2e. For example, for the path (number 15) along which emissions are 52 Gt CO_2e in 2020 and rapid reductions are delayed until around 2030, global mean temperatures exceed 2°C.

Finally, risks are not distributed equal across the envelope, even between paths with equal levels of median warming in 2100. We find that paths towards the upper end of the wider 'upper aerosol' envelope are associated with higher risks than those at the lower end. For example, Figure 2.4 compares the evolution of global mean temperature and the concentration of Kyoto greenhouse gases (expressed in terms of ppm CO_2e) for two paths with the same median warming in 2100, but different emissions in 2020 and 2050. For the path with low-end emissions (number 3) in 2020 (orange), there is a smooth increase in temperatures and a relatively low peak in the concentration of greenhouse gases at around 480 ppm CO_2e. For the path with high-end emissions (number 18), temperatures rise rapidly before stabilising. This is associated with a higher overshoot in concentrations of greenhouse gases to a peak of around 525 ppm CO_2e. The higher rate of temperature rise associated with the high emissions path implies less time for adaptation and potentially stronger climate impacts (Parry *et al*., 2007). More rapid warming and higher levels of greenhouse gases in the atmosphere also imply higher chances of exceeding trigger points, either physical (e.g. methane feedbacks) or biological (e.g. ecosystem damage), that could lead to damaging and irreversible impacts. Paths with higher overshoots rely upon being able to achieve rapid reductions in levels of greenhouse gases at a rate of almost 2 ppm CO_2e per year. Such a scenario would require rapid reductions in emissions to very low levels (e.g. the 'dip' in emissions at the lower bound of the envelope shown in Figure 2.2). A number of studies have questioned whether such a scenario is even physically possible given what we know about the climate system (e.g. Lowe *et al*., 2009). The economic and policy implications of this gradient in risk across the envelope are discussed in Part 3.

2.2.4 Uncertainty and its implications for targets

There are two main types of uncertainty that must be considered. The first is uncertainty in the emissions scenarios. For example, differences in the scenarios for emissions growth over the coming years have significant bearing on how rapidly emissions will need to be reduced in the longer term; more rapid growth in the shorter term means that stronger cuts will need to be made later on. The second type of uncertainty arises from our understanding of the science; that is, the response of the Earth system to anthropogenic emissions.

A full quantification of the uncertainties in emissions in 2020 and 2050 is beyond the scope of this study; however, we can approximate a lower bound on uncertainties through a comparison with other studies. However it is difficult to compare our findings directly with those from other studies, as none to date have systematically mapped such a wide range of emissions paths, in terms of both emissions in 2020 and peak dates, that are consistent with our climate goal. A review of previous studies is provided in Annex 1. The most relevant studies are those of Meinshausen *et al*. (2009) and the ongoing AVOID programme. In general, we find that the conclusions of our study are broadly consistent with previous studies (see Annex 1 for details), depending on the assumptions that are made. The level of emissions in 2020 is relatively robust (i.e. to within a few gigatonnes), under a range of plausible emissions and climate assumptions. However, we do see a strong sensitivity to assumptions about aerosol emissions. For example, both Meinshausen *et al*. (2009) and our study suggest that annual emissions of greenhouse gases in 2020 need to be well below 50 Gt CO_2e on lower aerosol assumptions; while studies with higher aerosol scenarios (e.g. the 'upper' aerosol scenario here and the AVOID programme[17]) allow more flexibility in 2020.

There is more sensitivity of emissions paths to the assumptions about 2050. A comparison shows that our 2050 targets are generally more stringent than those in other studies, including those reviewed in the IPCC Fourth Assessment Report (see Annex 1). This largely reflects the difference in assumptions about climate sensitivity and carbon cycle feedbacks. Our study drew upon recent estimates of these parameters that are consistent with the conclusions of IPCC (2007). However, we interpreted this difference between the studies as a real uncertainty in appropriate 2050 emissions targets, due to our understanding of the scientific uncertainty, which should be quantified. For the window of 2050 targets indicated by our study, we have suggested a range of uncertainty for each target of the order of ±5-10 Gt CO_2e. The scale of the uncertainties associated with the emissions paths and the science, and the related risks, highlight the need to reassess targets regularly as the evidence develops and to set targets for 2020 in such a way that they allow flexibility in subsequent action.

[17] Jason Lowe, personal communication

3. Mitigating climate change with reductions in greenhouse gas emissions: economic assessment of emissions targets[18]

Alex Bowen and Nicola Ranger[19]

Summary

This policy brief examines the risks, costs and feasibility of options for global emissions targets in 2020 and 2050. Part 1 provided background and Part 2 explored climate science constraints on targets for annual global emissions in 2020 and 2050. Part 3 examines the economics of targets.

Part 2 showed that, to have a reasonable chance (i.e. a probability of 50 per cent) of achieving a climate goal of avoiding a rise in global mean temperatures of more than 2°C above pre-industrial levels , global annual emissions of greenhouse gases must be reduced to between 40 and 54 Gt CO_2e in 2020, and then continue to decline, passing through a 'window' of around 6 to 17 Gt CO_2e in 2050. In a scenario with lower aerosol emissions over the coming decades , global emissions of greenhouse gases would need to be at the bottom end of the window in 2020 (i.e. below around 48 Gt CO_2e), and between 14 and 17 Gt CO_2e in 2050.

There are two important implications from Part 2 for an assessment of the economics of targets for emissions reductions: first, smaller reductions in annual emissions up to 2020 would have to be accompanied by much stronger action afterwards to achieve the climate goal; and second, the level of risk is not the same across the envelope of emissions paths. We draw the following conclusions in Part 3.

The policy goal of ensuring a reasonable chance of avoiding a rise in global temperatures of more than 2°C above pre-industrial levels is demanding. But, with well-designed policies applied consistently across countries, industries and greenhouse gases, several recent modelling exercises suggest that it is feasible. The studies imply that it is vital that cost-effective policies are implemented in a co-ordinated way around the world.

Lower targets (i.e. bigger reductions in emissions) are likely to be associated with higher costs of mitigation. But most studies suggest that, if a target can be hit at all, it need not cost more than a few percentage points of GDP – if policies are well-designed. The benefits from limiting the risks posed by climate change are likely to be much greater, making the necessary investment very worthwhile. And there are likely to be important co-benefits from action through, for example, reduced local pollution and increased energy security.

An ambitious long-term goal for climate change policies makes it imperative that a range of well-known market failures, particularly in relation to research, development and early deployment, are overcome. This could bring about a marked fall in emissions within a short period of time, as relevant market failures are tackled – correcting them does not necessarily require massive public spending or a lengthy period of investment or learning. Given the importance of innovation in driving economic growth over the long term, stimulating R&D in low-carbon technologies could also initiate a burst of entrepreneurial activity throughout the global economy, driving clean, green growth. There may also be periods of more rapid emission reductions in the future, particularly when low-carbon technologies become cost-competitive at scale in key sectors like power generation. But it is necessary to prepare the ground for such technological turning points.

Targets for annual emissions set at regular intervals and observations of carbon prices can be used to monitor and provide incentives to policy-makers to achieve the long-term climate goal that they adopt. It makes sense to choose targets for annual emissions that encourage early, co-ordinated and persistent action, taking advantage of the lower initial costs of emissions reductions and reducing the need for very rapid reductions in the medium to long term. The outlook for the costs of further reductions can then be re-assessed in the light of technological developments after a decade or so of experience. An early peak in global emissions – before 2020 – is desirable, especially if policy-makers conclude that a discount rate lower than the market interest rate is appropriate.

[18] The authors gratefully acknowledge helpful reviews of this Part of the policy brief by Andrew Gouldson and Dimitri Zenghelis.

[19] Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science, London, UK. The authors

[20] Where a 'reasonable chance' is defined as a probability of 50 per cent.

[21] Aerosol emissions, overall, tend to cool the climate. Annual emissions have been reduced strongly over the past few decades because of health and environmental concerns. We look at two possible future aerosol scenarios, both of which assume some proportionate reduction in aerosol emissions relative to emissions of carbon dioxide from fossil fuel consumption, but at different (though equally plausible) rates.

Delays in participation in a global regime for climate change policy are likely to increase significantly the costs of achieving the target, without benefiting the 'late adopters', and may make the target impossible to reach.

More rapid reductions later have a higher likelihood of running up against constraints in time and costs – for instance, of installing new capital and developing new technologies – especially if policy has not earlier set the appropriate incentives for businesses.

Based on the science and economics, we conclude that, to limit the probability of exceeding warming of 2°C to 50 per cent, policy-makers should aim for annual global emissions to be between 40 and 48 Gt CO_2e by 2020. This is equivalent to limiting global annual emissions to levels in 2020 that would be between 8 and 30 per cent higher than 1990 levels. Although our scientific assessment suggests that permissible annual emissions could reach 54 Gt CO_2e in 2020 under some conditions, such a scenario would be subject to greater uncertainty and assumptions. In particular, such an emissions paths (which would result from 'delayed action' or low early ambitions for reductions) would require relatively high levels of aerosol emissions (which offset some warming) in the future, as well as an ability to reduce emissions to very low levels by 2050 (as low as 6 Gt CO_2e) and a reliance on unproven assumptions about the ability of the Earth system to recover quickly after 'overshooting' a target level for the atmospheric concentration of greenhouse gases. It would also require very strong and costly global emissions reductions after 2020. Therefore, an upper bound for annual emissions in 2020 of 48 Gt CO_2e would be more prudent. Further, our analysis suggests that it would now be politically unfeasible and probably prohibitively expensive to reduce annual global emissions to much less than 40 gigatonnes (Gt) of CO_2e by 2020 (i.e. close to 1990 levels). For example, reaching 40 Gt CO_2e would require halting emissions growth today and then reducing emissions at a rate of more than 3 per cent per year from, at the latest, 2014 onwards (by comparison, between 2000 and 2005, annual emissions grew at a rate of more than 2.5 per cent per year). Such a rate of reduction may be technically feasible, but would require very strong and immediate policy action, entailing high carbon prices and significant early scrapping of high-carbon plant and machinery.

3.1 Introduction

The policy goal of ensuring that we have a reasonable chance of avoiding global warming of more than 2°C above pre-industrial levels has now been recognised by a number of Parties to the UNFCCC. Part 2 showed that to have a reasonable chance (i.e. a probability of 50 per cent, or even-odds) of meeting this goal, annual global emissions must be reduced to between 40 and 54 Gt CO_2e in 2020, and then continue to decline, passing through a 'window' of about 6 to 17 Gt CO_2e in 2050. Under a plausible scenario of lower future emissions of aerosols, greenhouse gas emissions would need to be cut even more strongly in 2020 (to at most 48 Gt CO_2e). The rapid turn-around in the trend of global emissions required by any of these options demands a fundamental transformation in the functioning of the global economy. Each emissions path would require major changes in how energy is produced and how efficiently it is used, in the technologies used in several other industries, and in land use. Can those changes be carried out quickly enough to achieve the emissions cuts implied by the paths and targets? If so, how costly will they be?

If the changes are very expensive or even not technically feasible, then policy-makers could be in danger of undermining the credibility of the target and hence of their intentions. Also, it would risk encouraging an inadequate level of preparation for adaptation to climate change. If the changes are feasible but very costly, that could also undermine public support for a strong policy regime on climate change and could bring into question the wisdom of the goal of a 2°C ceiling for the rise in global temperature. But if the changes are feasible at a moderate cost, the collective international judgement reflected in the adoption of a 2°C climate goal makes sense. Considerations of feasibility and cost can help policy-makers identify what has to be done to make it likely that the world will stay below the ceiling. They can also help policy-makers decide which of the family of emission paths consistent with the climate goal are preferable, and hence what intermediate targets for annual global emissions would be useful.

There are two important conclusions from Part 2 for the economic assessment of targets: first, a lower level of ambition (i.e. smaller emissions reductions) in the near term means stronger action would be required after 2020; and second, the level of risk is not equal and constant across the envelope of emissions paths. In this Part, we review the relevant evidence and draw conclusions about where within the envelope policy should be aimed.

3.2 Costs and feasibility of emissions reductions

3.2.1 Why is mitigation likely to entail costs?

Costs are likely to arise from various sources. First, low-carbon energy production – from renewable sources, for example – is likely to be more expensive per unit of energy produced, at least to begin with, before experience with new technologies drives costs down. The up-front burden on costs also in part reflects the fact that many renewable technologies have high capital expenditure and development costs relative to traditional fossil fuels, but much lower operating costs, because they do not require large fuel inputs. Similarly, reductions in the emissions of greenhouse gases that are produced in other industrial processes may involve at least temporarily lower productivity. Second, switching to a low-carbon economy will involve earlier scrapping of some capital equipment and additional investment in plant, buildings and equipment embodying low-carbon technologies, possibly crowding out some spending on goods and services for consumption. The IEA estimates that incremental energy-related investment of around US$10.5 trillion will be required over the period between 2010 and 2030, amounting to about 0.5 per cent of world GDP by 2020 and 1.1 per cent of GDP by 2030 (IEA, 2009).[22] Third, 'making the polluter pay' will entail higher prices (relative to incomes) for goods and services that remain emissions-intensive, adding to consumer and downstream producer costs. Fourth, the sharper increases in the intensity of climate change policies have higher risks of disrupting economies and creating unemployment. In other words, a sudden change in the policy regime, such as the imposition of much higher carbon prices, can amount to an adverse supply shock – similar in effect to the sharp increases in oil prices in the 1970s and 1980s.

3.2.2 Non-climate benefits helping to offset costs

However, costs are likely to be offset, in part, by benefits that are unrelated to climate change, such as greater energy security and lower local air pollution. The IEA projects the reduction in local air pollution, in its scenario for stabilisation of atmospheric concentrations of greenhouse gases at 450 ppm CO_2e, to be worth around US$100 billion per year by 2030. Further, if climate change policies are to be implemented in a cost-effective way, policy-makers will have to tackle various market failures alongside the key market failure brought about by the externality of greenhouse gas emissions.

Tackling market failures can bring down costs substantially, and in some estimates lead to net economic gains even before the climate change benefits are considered. Resolving the information and incentive problems that lead to inefficient use of energy provides a good example. Another is timing public infrastructure investment for the low-carbon economy so as to counteract unexpected adverse shocks to private-sector demand – which, in a nutshell, is the case for a 'green' fiscal stimulus: using resources that would otherwise be under-utilised to fight climate change (see, for example, Bowen *et al*., 2009). Governments have in practice devoted significant shares of their stimulus packages to infrastructure and other spending designed to reduce emissions of greenhouse gases. The IEA (2009) ascribes one-quarter of the downward revision to its emissions projection for 2020 (compared with its projection a year earlier) to government stimulus spending to promote low-carbon investments and other new climate policies. Revenues from carbon pricing could be used to reduce distortionary taxation elsewhere in the economy.

Finally, climate change policies, if they stimulate innovation generally, can bring about an increase in underlying growth rates, as seen in past transformative episodes such as the advent of the steam engine and electrification. This is because innovation in new technologies is likely to have greater potential to induce cost reductions from learning and experience than the innovation in mature fossil-fuel technologies that it might crowd out, while the potential for knowledge and technology spillovers to other sectors is correspondingly much larger.

[22] These investments should, however, earn a competitive social return after taking into account the climate change risks that will be averted (and, in the private sector, a competitive private return if carbon prices, incentives for research, development and deployment of low-carbon technologies, and other policy instruments are all set correctly).

3.2.3 Why do tighter targets mean higher mitigation costs?

Estimates of the costs of mitigation suggest that they will be higher for tougher emissions reduction targets. The message is the same whether the estimates are derived ‘from the bottom up’ – from engineering-based studies of abatement cost curves, sector by sector – or ‘from the top down’ – from macroeconomic models that take into account the feedback of climate change policies on the rest of the economy (as included in many so-called integrated assessment models (IAMs) that combine economic analysis with climate projections). It takes time to change the capital stock that currently embodies high-emissions methods of production, to increase the productivity of existing low-emissions technologies and to invent new ones. During that time, cumulative emissions mount, unless choked off by very large increases in the prices of emissions-intensive goods and services. With a very low target, there would simply not be enough time for the necessary technological progress and investment to introduce enough low-carbon energy into the global economy.

None of the ‘bottom-up’ and ‘top-down’ estimates of mitigation costs take all these factors into consideration, so there is still a significant degree of uncertainty about the relationship between costs and the stringency of the long-term target. Stern (2006) concluded that the costs of mitigation consistent with a stabilisation target of 500-550 ppm CO_2e were likely to be of the order of 1 per cent of annual GDP by 2050, within a range of +/- 3 per cent. Studies of mitigation costs have suggested that they would not rise very sharply with increased stringency of the long-term target, up to a point when the required technological changes become infeasible. That point, Stern (2006) concluded, would very probably be reached if the target was as low as 450 ppm CO_2e, so it proposed that level as the lower bound of the range for the stabilisation goal.

Since the Stern Review (Stern, 2006) was published, the IPCC Fourth Assessment Report (2007) has surveyed the literature, finding that IAM-based estimates of costs in 2050 for stabilisation at 650 ppm CO_2e ranged from 2 per cent of GDP in 2050 to -1 per cent (i.e. net non-climate benefits); for stabilisation at 550 ppm CO_2e costs ranged from 4 per cent to just under zero; and for stabilisation at 445 to 535 ppm, CO_2e costs ranged up to 5 per cent. The work of the United States Climate Change Science Program (USCCSP) on scenarios for greenhouse gas emissions and atmospheric concentrations came to a similar conclusion about the rise in expected mitigation costs as the target becomes tougher (USCCSP, 2007). It reported that the costs in 2060 of heading towards a target of 450 ppm CO_2 (around 525 ppm CO_2e) ranged from 1.9 to 6.7 per cent of GDP across the three IAMs that were considered. That compared with only 0.2 to 2.3 per cent if the target was a less demanding 550 ppm CO_2 (around 670 ppm CO_2e).

3.3 The state of the evidence related to 2°C

Part 2 showed that, on central projections, the 2°C goal is equivalent to keeping atmospheric concentrations of greenhouse gases below roughly 500 ppm CO_2e, and eventually falling to below 450 ppm CO_2e. This objective is more demanding than those explored previously by most economic modelling exercises. For example, only six out of 177 mitigation scenarios reviewed by the IPCC (2007) considered a stabilisation target in the range of 2.5–3.0 W/m^2 for radiative forcing (concentrations of 445–490 ppm CO_2e); all the others considered higher targets. Since the publication of IPCC (2007), several research groups have investigated the feasibility and costs of more ambitious targets in line with the 2°C goal, or are in the process of doing so. Examples include the ADAM project, the RECIPE project, the most recent round of the Stanford Energy Modeling Forum and, following a rather different approach, McKinsey & Company’s ‘Pathways to a low-carbon economy’.[23]

3.3.1 Feasibility

Several models suggest that such climate goals and targets are feasible, but only under certain strong assumptions about the scope of climate change policies and technological progress. For example, the recently completed ADAM project (Knopf *et al*., 2009) investigated the challenge using five different global energy-environment-economy models with regional detail. It concluded that “low stabilisation is feasible in terms of technologies and moderate in costs” but only if “the full suite of technologies is available and effective policy instruments are applied”. The RECIPE project, using three different models (one overlapping with the ADAM project), has come to a similar conclusion (Edenhofer *et al*., 2009). This tells us that, to achieve a 2°C goal, appropriate policies to provide incentives for emissions reductions and to bring forward low-carbon technologies must be put in place with urgency.

[23] Adaptation and Mitigation Policies; Supporting European Climate Policies http://www.adamproject.eu/; RECIPE project, http://www.pik-potsdam.de; Stanford Energy Modeling Forum 22, various papers in press for *Energy Economics*; McKinsey & Company (2009).

Feasibility is influenced strongly by whether overshooting the ultimate greenhouse gas or temperature stabilisation level is acceptable. In Part 2, none of the emissions paths resulted in overshooting the temperature goal and then returning below. Paths with overshooting temperatures are associated with higher climate impacts and there is little evidence that it would be possible to reduce concentrations and hence global temperatures at rates fast enough to avoid potentially dangerous impacts (Stern, 2006; Lowe *et al*., 2009).

The 2°C emissions paths in Part 2, like many other studies (e.g. den Elzen *et al*., 2007), do however assume that atmospheric concentrations of greenhouse gases peak and then decline. Reducing concentrations does not necessarily require net anthropogenic emissions are negative, but simply that net emissions are lower than the Earth's capacity to extract greenhouse gases from the atmosphere through the natural carbon cycle (which is itself a function of concentrations). However, the higher the concentration peaks, the lower the level of emissions that would need to be reached subsequently to achieve the 2°C goal, and the more rapidly this would have to be achieved. For example, our path with the highest emissions in 2020 that still met our climate goal, peaked at around 525 ppm CO_2e and then required global emissions to be reduced to just 6 Gt CO_2e in 2050. The feasibility of such a scenario is questionable. For example, 6 Gt CO_2e is equivalent to the level of greenhouse gas emissions from agriculture alone today. Let us assume that innovations in the agricultural sector would enable us to stabilise agricultural emissions against the background of rising food demand resulting from the projected increase in global population of 50 per cent by 2050 and rising standards of living, i.e. a decrease of at least one-third in the emissions intensity of agriculture (Barker *et al*., 2009); achieving such a scenario would still require net zero emissions from all other sectors by 2050.

All of the paths described in Part 2 that met our climate goal required emissions to be reduced to around 6 Gt CO_2e eventually; for paths with bigger earlier reductions, this level must be reached by around 2100. Some question whether such low levels of emissions are possible at all, given the food needs of the rising population, without unproven and potentially costly carbon sequestration technologies. If this proves to be the case then meeting the 2°C climate goal may be economically infeasible. Economic studies that incorporate overshooting of the long-term concentration of greenhouse gases typically rely on 'negative-emissions' technologies in some sectors, for example, large-scale biomass with carbon capture and storage. Geo-engineering solutions could perform the same function. But the feasibility of rapid, large-scale implementation of unproven technologies, including geo-engineering approaches, is uncertain, and there are significant risks and governance issues associated with many of them. Time and experience (often proxied in projections by cumulative output from the new technology) are required for the learning-by-doing, learning-by-use and induced technical progress that reduce costs of low-carbon technologies and hence encourage their diffusion throughout the global economy. The costs and doubts about the feasibility of scenarios requiring rapid deployment of negative-emissions technologies at scale, compared with the costs of strong early action, point towards the benefits of selecting a target for 2020 that lies in the lower half of the envelope in Part 2.

A number of model exercises also cast doubt on whether the ambitious rates of emissions reductions over the next few decades required to avoid a temperature rise of more than 2°C are feasible. Some of the models included in the EMF22 exercise are unable to generate paths consistent with a target of stabilising concentrations at 450 ppm CO_2e even with the full participation of all regions in the world. Blanford *et al*. (2009), for example, found that a radiative forcing target equivalent to 450 ppm CO_2e "cannot be met even allowing for full participation [of all countries] and overshoot during the entire 21st century". They pointed out that this finding reflects the 'speed limits' imposed in their model on the rate of transformation of regions' energy systems, the strong growth of 'business as usual' emissions that they projected, and the absence of negative-emissions activities such as biomass with carbon capture and storage and afforestation. Tol (2009) found that the target of avoiding a temperature increase of more than 2°C is infeasible "under any but the most advantageous of assumptions". In his model FUND, a climate sensitivity of no more than 2.5°C per doubling of ambient CO_2 was required, together with a carbon tax starting at over US$270/tonne CO_2 in 2013, applied to all greenhouse gases and all countries, and rising at the discount rate. Such results have drawn attention to the need for strong early action, including the early imposition of substantial carbon prices and support for innovation, to overcome the 'speed limit' restrictions on economic transformation and for the development of carbon-neutral or carbon-negative technologies in time to rein back rapidly any overshoot in atmospheric concentrations of greenhouse gases. They have also implied the need to be prepared to revise targets and policy instrument settings if experience bears out the less optimistic studies.

However, the feasibility of ambitious targets is supported by the 'bottom-up' analyses of McKinsey & Company (2009), which focused on what detailed technological changes would be necessary up to 2030 to ensure that the world was on a path consistent with keeping below the 2°C ceiling. These analyses have tended to draw more attention than past studies to the scope for low- or negative-cost mitigation, if various market failures affecting the use of energy are tackled so as to improve energy efficiency significantly. Thus McKinsey & Company (2009) identified potential reductions of over 10 Gt CO_2e per year by 2030 that would have negative costs. These included improvements in energy efficiency in residential electronics and other appliances, greater waste recycling, clinker substitution by fly ash in industry, insulation retrofits in businesses, and changes in tillage and residue management in agriculture. 'Bottom up' estimates of this sort have been criticised for downplaying the difficulties of implementing improvements and, in some cases, for confusing engineering possibilities under ideal conditions with cost-effective improvements in real-world conditions (e.g. Joskow and Marron, 1992). But another way of stating this critique is to emphasise that correcting market and management failures is not necessarily easy, even where the resource costs are small. Effective policies to combat climate change must acknowledge that fact.

3.3.2 Mitigation costs

Studies that have concluded that meeting the 2°C climate goal is feasible have suggested that it will entail costs of less than 5 per cent of GDP and as low as 1 per cent of GDP (or even less if climate change policies stimulate aggregate demand in a demand-constrained world economy):

- den Elzen *et al*. (2007) investigated a set of feasible multi-gas emissions paths for stabilisation at 450 ppm CO_2e (peaking at 510 ppm CO_2e), 550 ppm CO_2e and 650ppm CO_2e. They estimated that net present value (NPV) of mitigation costs across the century (with a discount rate of 5 per cent) would range from 0.2 per cent of cumulative GDP in the case of the highest target to 1 per cent in the case of the lowest.
- Knopf, *et al*. (2009) considered five IAMs with different characteristics and found that ultimate stabilisation at 450 ppm CO_2e, if feasible, would cost less than 1.5 per cent of GDP (cumulated to 2100). Stabilisation at 400 ppm CO_2e would be, at most, around one percentage point of cumulative GDP more expensive than stabilisation at 450 ppm CO_2e; that could be regarded as the premium to be paid to reduce the likelihood of exceeding the 2°C ceiling by some 30 percentage points.
- Rao *et al*. (2008), using two other IAMs, found that the costs of aiming for stabilisation at around 450 ppm CO_2e would be about 3 per cent of GDP by 2050, and 5 per cent by 2100.
- Edenhofer *et al*. (2009), after examining three IAMs, concluded that the discounted welfare costs of stabilising at 410 ppm CO_2 (a target of broadly similar ambition to the 450 ppm CO_2e target) would be around 0.8 to 4 per cent of baseline global GDP.
- Calvin *et al*. (2009) developed a scenario with strong policies on land-use that met a 450 ppm CO_2e target for stabilisation[24], but only with a very high carbon price.

More generally, there are some important lessons about the feasibility of, and costs associated with, tough targets to be learnt from mitigation studies. Crucially, when tough targets have been feasible in models, they have not been very much more expensive to reach than less demanding targets, especially in the early years. That reflects the broadly 'L-shaped' relationship between mitigation costs and the ultimate stabilisation level found in most modelling exercises. The more demanding targets require faster accumulation of low-carbon capital stock and investment in low-carbon innovations and stronger carbon price signals, but, as the transformation of the capital stock is largely restricted to a few sectors like energy and transport, the extra costs are limited. However, at some point (the apex of the 'L-shape'), as lower and lower stabilisation targets are considered, the necessary transformation in those sectors takes too long to cut emissions quickly enough, leaving only the option of choking off demand for high-carbon goods and services with a very high carbon price (some models based on the analysis of marginal abatement costs have not fully allowed for this possibility and hence have run into the infeasibility barrier at higher stabilisation levels than they would have otherwise).

[24] The target was actually expressed in terms of a radiative forcing of 2.6 W/m².

The key factors determining costs include:

- the rate of growth of emissions of greenhouse gases under 'business as usual' – the more rapid this rate is, the bigger the challenge of decarbonisation;
- the speed at which the productivity of low-carbon technologies increases with spending on research, development and deployment, investment, time and experience (or cumulative production) – some models have still excluded induced innovation and endogenous growth, whereas models that included them tend to have projected lower costs of action;
- the scope for demand-side adjustments – in other words, the degree of substitutability of low-carbon goods and services for high-carbon ones in consumption and production: estimates of price elasticities of demand derived from past energy price shocks may not be a good guide to the elasticities in a world of credible, long-term carbon pricing;
- the scope for 'free lunches' from greater energy efficiency without changing the pattern of final production;
- whether marginal abatement costs are equalised across firms, sectors and countries; and
- whether land-use is subject to strong policies, with deforestation reversed and the use of land for food production and biomass prevented from crowding out forest 'sinks'.

It is important to note that even the optimistic estimates of costs do not consider the non-zero possibility of a breakthrough invention that transforms the outlook for energy and emissions (e.g. power from nuclear fusion, sequestration of greenhouse gases from the atmosphere). The full probability distribution of possible mitigation costs includes such scenarios, but also scenarios at the other end of the spectrum in which much more of the burden of emissions reductions has to be carried by substitution of consumers and companies away from emissions-intensive products. Also, few modelling exercises have considered the possibility of climate change policies 'kick-starting' innovations with more widespread applicability across the economy, unleashing a period of 'Schumpeterian' growth.

3.3.3 The impact of policy on costs and feasibility

Feasibility and costs are also influenced heavily by how well climate change policies are designed. To achieve tough targets for emissions reductions, policies need to cover all countries, sectors and greenhouse gases, and to correct a range of market failures in innovation, information provision, finance, land rights and other areas, to achieve adequate energy efficiency gains and technological progress. And success requires policy-induced technological progress to bring down the costs of low-carbon energy technologies, without the crowding-out of innovation elsewhere in the economy increasing costs in other sectors sufficiently to outweigh the gains. Potential spillovers across sectors could be substantial, creating a significant externality because the private sector is likely to under-invest in new technologies without government intervention or regulation. Lessons can be drawn from the history of defence spending, where public investment has led to technology leaps in products as different as electricity turbines, the internet and ink-jet printers.

One key policy consideration is how soon all major emitting countries start to take strong action against climate change. Recent studies have made clear that delay increases the overall costs of reaching any particular target and may render it impossible to achieve (Krey and Riahi, 2009). Delay means that atmospheric concentrations of greenhouse gases would rise to a higher level, so that a larger drop in annual emissions (to a level below that which would otherwise be required) is then needed to hit any stabilisation target. The larger drop in annual emissions is likely to increase total costs, as investment would be subject to adjustment costs that rise more than proportionally with the volume of investment. Delay in implementing policies to correct market failures responsible for energy inefficiencies reduces the net present value of these 'negative cost' options.

Several models have implied that the carbon price should rise steadily over time, ramping up the intensity of decarbonisation activities gradually. But they have also implied that a non-zero carbon price is needed straight away; delay wastes the opportunity for immediate reductions in demand for carbon-intensive products. These models have usually assumed that the carbon price rises at a rate closely related to the discount rate, which is itself related to average long-term real rates in financial markets.[25] If policy-makers conclude that a lower discount rate is appropriate when considering very long-term intergenerational issues (Stern, 2008), then they should prefer to accelerate investment in low-carbon capital stock and start to bring emissions down earlier. Carbon prices would have to be introduced at a higher level initially but would not need to rise as rapidly afterwards. Finally, early strong action to reduce emissions maintains the option of switching to a lower target later if new scientific or economic analysis warrants it. As the costs are likely to be lower in the early years than later, it makes sense to start out on an ambitious path, re-assessing the outlook for costs in the light of technological developments after a decade or two of experience.

3.3.4 Recent changes in model assumptions

At the same time as modellers have developed the analysis of the costs and feasibility of tougher targets, the economic environment has been evolving and key parameters in cost estimates have been subject to re-assessment. Global annual emissions of greenhouse gases have continued to push up the concentrations in the atmosphere – by about 2.5 ppm CO_2e per year this decade, at least until the global downturn arrived, which made any given target more difficult to achieve. Projections of 'business as usual' emissions of greenhouse gases have tended to be revised upwards, reflecting both observed trends in emissions this decade, and sharp upward revisions in the long-term prospects of China and India following their unprecedented recent growth rates; this is associated with a more rapid increase in the use of coal in the absence of strong climate change policies (see, for example, Sheehan, 2008; Garnaut, 2008). The probability of long-term, low-growth trajectories for world GDP may have been overestimated in the past (Webster *et al*., 2008).

However, the onset of the global economic slowdown may lead to a reassessment. The IEA has recently revised down the level of energy-related CO_2 emissions in 2020 by 5 per cent compared with its reference scenario a year earlier (IEA, 2009). One modelling group has already revised down its long-term GDP projections (Paltsev *et al*., 2009). These authors also noted that renewable energy technologies appear to be more viable and are being deployed more rapidly than previously assumed, while the political barriers to an expansion of nuclear power seem to have lessened. However, they argued that both nuclear power and carbon capture and storage are likely to be more expensive than previously thought. Overall, they concluded, the costs of meeting tough targets for emissions reductions are likely to be somewhat higher than they thought a few years earlier.

Blanford *et al*. (2009) found that upward revisions of the outlook for growth in the developing world over the long term more than outweigh the impact of even pessimistic assumptions about the consequences of the current global slowdown. It is clear that if the current growth aspirations of the developing world are to be met, the challenge for policy-makers is tougher.

3.4 Act early or delay?

The evidence strongly supports the conclusion that the benefits of early action outweigh those of delay. The science shows us that, for any given temperature increase ceiling, we have a choice of starting emissions reductions sooner and reducing them gradually (but persistently) over the longer term, or delaying action and making rapid reductions later on. For example, Part 2 showed that at the bottom end of the envelope in 2020 for paths that are consistent with a reasonable chance of avoiding a temperature rise of more than 2°C, with emissions peaking in the next few years and then falling to 40 Gt CO_2e in 2020, emissions would need to be reduced at an average rate of 3 per cent per year between 2020 and 2050. At the top end of the envelope in 2020, with action delayed such that emissions peaked at 54 Gt CO_2e in 2020, emissions would need to be reduced at a rate of 7 per cent per year between 2020 and 2050. What does the economics tell us about which path is preferable?

The benefits of early action were illustrated by den Elzen *et al*. (2007) in their study of families of emissions paths designed to achieve specific long-term goals. They found that, for a target of stabilisation at 450 ppm CO_2e, paths requiring early abatement of emissions tend to have lower costs over the century in net present value terms than paths that reach the same concentration target but with much later abatement, unless a high discount rate is used (8 per cent per year or more). The early-abatement paths reap benefits from encouraging more technical progress early on and avoiding the need for very sharp annual reductions in emissions along the way, although costs in the early years may be higher than with delay. The authors' 'early action, average change' option entailed peak emissions by the middle of the next decade, and is around 5 per cent cheaper in terms of discounted cumulative GDP costs (using a 5 per cent discount rate) than the delayed response option, assuming an IPCC SRES B2 'business as usual' scenario (with the higher 'business as usual' path in the SRES A1b scenario, the delayed response option could not reach the target).[26]

[25] Specific assumptions about discount rates and/or the rate of interest for cap-and-trade banking and borrowing differ significantly. For example, Paltsev *et al*. (2009) used a discount rate of 4 per cent, while Goettle and Fawcett (2009) used 5 per cent, and Knopf *et al*. (2009) used 3 per cent.

[26] The den Elzen *et al* study is based on a model in which different emissions trajectories are costed using detailed marginal abatement cost curves. It does not take into account costs incurred elsewhere in the economy as a result of macroeconomic adjustments. Some argue that this is an important caveat (see, for example, Morris *et al*., 2008).

Delays by some high-emission countries in adopting strong policy would have the disadvantages described in the preceding discussion, but would also risk some displacement of carbon-intensive activities from the early to the late adopters, weakening the effects of early action by other countries and distorting the location of production. Hence if a country is late in adopting formal action, it is important that agents in the private sector anticipate the eventual policy regime and hence stop investing in high-carbon capital stock before formal action is initiated; otherwise, they waste resources building up stocks of the wrong type of plant and equipment (Blanford *et al*., 2009; Bosetti *et al*., 2009). Strong early action provides a clear signal to business that the world will become carbon constrained and profits can be made by investing in low-carbon products and processes. Countries have an incentive to be 'early adopters' of policy, because starting early to transform their capital stock to low-carbon technologies means that they will have less need to buy emissions quotas or offsets from other countries later. Blanford *et al*. (2009), for example, found that if the BRIC countries[27] committed now to strong policy actions from 2030 (aiming for a target stabilisation of 550 ppm CO_2e), that would reduce the costs of action for them by around 30 per cent compared with delay and no anticipation; it would reduce costs for the OECD[28] by some 50 per cent. Van Vliet *et al*. (2009) came to a similar conclusion, with delayed participation in the 550 ppm CO_2e (3.7 W/m2 radiative forcing) stabilisation case costing up to 90 per cent more than full participation.

Some economists have been sceptical about the plausibility of fulfilling one or more of the requirements for aggressive abatement of greenhouse gas emissions (see, for example, Helm, 2009; Paltsev *et al*., 2009; Tol, 2009). And some costs have probably been underestimated in the past, such as the those of coping with the intermittency of most renewable energy sources and of transforming power distribution networks. But the model results that have suggested that the world can stay below the 2°C ceiling at moderate cost have not ignored the fact that significant changes are nevertheless required in the structure of economies; they have spelled out clearly the scale of what policy-makers have to do if such an ambitious target is to be achieved.

Most modelling exercises that found the 2°C climate goal is feasible have suggested a gradual slowing in emissions growth until a peak is reached, followed by an average rate of emissions reduction in the decade or two after the peak of the order of 1.5 to 3 per cent per year (the IEA, for example, envisaged energy-related CO_2 emissions falling by about 1.5 per cent from a peak just before 2020 until 2030). With an initial step change from the correction of related market failures, the initial deceleration of emissions could be sharper than most of these exercises envisage. After the peak, annual rates of decline tend to increase gradually. Hence between 2040 and 2050, the annual rate of reduction in many models has been considerably higher, as the power generation sector decarbonises. In one set of model results in Knopf *et al*. (2009), the maximum rate reached nearly 7 per cent for CO_2 emissions. In Edenhofer *et al*. (2009), the maxima for a decadal average rate of reduction in CO_2 emissions from fossil-fuel burning across their three models varied from around 5 to 6 per cent.

Studies that have allowed for full cost optimisation have shown the possibility of rapid rates of emissions reductions at technological 'turning points', so imposing arithmetical constraints on the rates may be too restrictive. Schmidt and Marschinski (2009) noted that new technologies (e.g. mobile telephones) have often reached a stage where suddenly they have diffused rapidly through the economy, because of economies of scale in production and rising returns to R&D as output rises. Using a partial-equilibrium model of energy generation with endogenous R&D and explicit sources of multiple market failure, they found that multiple equilibria are possible, and policy instruments have to be used to push the world economy towards an equilibrium with high penetration of renewable energy use. With the right policies, though, the switch can be fast. But rapid percentage rates of decline are only possible if sufficient technical progress has been induced in low-carbon technologies and firms have not earlier locked themselves into high-carbon capital stocks. Also, the absence of the relevant 'network economies' (e.g. existence of a network of battery recharging stations or electricity grids suitable for local co-generation) may have to be rectified with the help of public intervention. Hence the diffusion of new techniques, plant and equipment may not be as rapid as implied by simple models of technology choice. That means that high rates of decline are less likely to be achieved in the early years of adoption of climate change policies, immediately after the 'low-hanging fruit' associated with market failures have been harvested.

[27] Brazil, Russia, India and China.

[28] The OECD was assumed to act immediately in this scenario.

If actions are delayed, sharp declines later will be more difficult, and the delay itself is likely to bring into question the commitment of policy-makers to a policy regime, thus slowing private sector preparation for abatement. Models that have examined the consequences of delayed action by some countries have often had very rapid rates of emissions reductions when action is finally taken, but that has depended on those countries being able to acquire low-carbon technologies rapidly from countries that adopted policy earlier and drove the technological developments necessary. Calvin *et al*. (2009), for example, had a scenario in which developing countries (excluding India, China and Brazil) join late and then reduce emissions by over 30 per cent per year on average for 15 years. Such approaches are more expensive, both for the late adopters (in most scenarios) and the world as a whole (in all). From the perspective of private firms, business and regions that delay in participating risk missing out on the opportunities being created in the new markets for low-carbon products and are less likely to be able to influence product standards.

The arguments for early introduction of policies to reduce emissions can be summarised as follows:

- early action induces innovation sooner, by giving learning, experience, scale economies and networks time to evolve – it recognises that the diffusion of new technologies is not instantaneous even when they have become broadly cost-competitive with existing ones;
- early action globally avoids piecemeal application of policies and the displacement of greenhouse gas emissions to late adopters of policies (carbon leakage);
- early action allows policy-makers to establish the long-term credibility of the policy framework sooner, encouraging firms to pursue innovation and market opportunities in low-emissions technologies and products; and
- early action allows more gradual and hence less expensive capital scrapping and retrofitting.

3.5 Assessing the options for a 2°C path

Part 2 of this briefing concluded that to have a 50-50 chance of avoiding a rise in global mean temperature by more than 2°C above pre-industrial levels, global emissions would need to stay within an envelope passing through windows extending between roughly 40 and 54 Gt CO_2e in 2020, and between 6 and 17 Gt CO_2e in 2050. Paths near the upper end of the window in 2020 would need to be near the lower end of the window in 2050, and vice versa. Different paths passing through the envelope will have different implications for the feasibility and economic costs of action. If lower levels of future aerosols are assumed, tighter 2020 targets would be required; in this case, keeping to below 48 Gt CO_2e (and 14 – 17 Gt CO_2e in 2050). Part 2 also showed that paths with lower ambition (i.e. smaller emissions reductions) in 2020 are associated with higher risks. This section explores how feasibility varies across the envelope of emissions paths and considers whether the envelope should be narrower when relative economic costs and risk are taken into account.

3.5.1 Feasibility of the 40 to 54 Gt CO_2e window

It is impossible to say with certainty what is feasible in terms of global emissions reductions. In the past, emission reductions of more than 1 per cent per year have been rare. France's nuclear programme from the late 1970s helped achieve an average annual reduction in total fossil fuel emissions of 0.6 per cent between 1977 and 2003; the UK 'dash for gas' in the 1990s led to an average annual reduction of 1 per cent per year from 1990 to 2000. It took a prolonged economic crisis in the former Soviet Union to produce an annual average reduction of 5.2 per cent between 1989 and 1998 (Stern, 2006). But these examples can be misleading; never before has the world deliberately attempted to achieve strong emission reductions goals. Even so, there are constraints on the pace of reductions. den Elzen *et al*. (2007) surveyed 40 SRES non-climate-policy and 18 post-SRES mitigation scenarios and found that the maximum average annual rates of reduction over a decade were typically 2-3 per cent (and the highest rate reported was 4.5 per cent).

Rapid reductions in emissions are likely to be possible where appropriate policies have been put in place to make it profitable for firms to switch their investment to capital equipment embodying low-carbon technologies. For example, one modelling study suggested that global emissions reductions at rates of the order of 7 per cent per year may be possible if the appropriate technologies become available at scale. However, our review of the literature has led us to suggest that emissions targets above the 40 to 54 Gt CO_2e range are likely to make the 2°C climate goal impossible to reach, requiring unrealistically high rates of emissions reductions either in the early years (for the 40 Gt CO_2e target) or towards 2040 to 2050 (for the 54 Gt CO_2e target).

Keeping emissions below 40 Gt CO_2e in 2020 would give a better chance of avoiding global mean temperature from rising above 2°C, but such a path looks politically infeasible. Achieving 40 Gt CO_2e in 2020 alone assumes that emissions peak in 2014 at 48 Gt CO_2e (1 Gt CO_2e below our baseline estimate) and then fall at a rate of 3 per cent per year to 2020. While not technically infeasible, this is a very ambitious scenario, requiring very strong and immediate policy action entailing high carbon prices and significant early scrapping of high-carbon plant and machinery. For emissions to fall to less than 40 Gt CO_2e in 2020, say to around 38 Gt CO_2e, the rate of reduction would need to increase to 4 per cent per year from 2014. Alternatively, emissions could peak earlier or at a lower level, effectively stabilising emissions at 2010 levels and declining from there. Such action would require a complete turnaround in global energy systems and a reframing of economic development within only one or two years. This seems highly unlikely in the light of the growth rate in emissions of greenhouse gases of 2.6 per cent per year between 2000 to 2005 (excluding CO_2 from land-use changes).

If global emissions are above about 54 Gt CO_2e in 2020, very high rates of emissions reductions after 2020 would be required, and very low emissions levels would have to be reached by 2050. Our emissions path that peaked at 54 Gt CO_2e around 2020 would require emissions to be reduced at a rate of 5 per cent per year between 2020 and 2050 to offer a reasonable chance of achieving the 2°C climate goal. In this scenario, emissions would need to be reduced to just 11 Gt CO_2e in 2050, not far from the floor level set by our assumptions about agricultural emissions. With a target in 2020 of more than 54 Gt CO_2e, subsequent annual emissions reductions would have to be close to, or exceed, the maximum rates of emissions reductions typically seen in models to date, and would need to persist for longer. It is not possible to say that such rates are infeasible; models are generally not designed to assess what the maximum reduction rates could be (some impose a maximum a priori). Cost modelling exercises have, however, suggested that such high rates are unlikely to be optimal.

Beyond modelling, commonsense suggests that achieving very high rates of emissions reductions immediately after the peak is unlikely to be possible. For example, if we conduct a simple thought experiment, a 7 per cent annual rate of reduction is equivalent to a 52 per cent reduction in absolute emissions over the first 10 years, globally. This would mean very ambitious cuts across almost all sectors. For example, it is equivalent to a 60 per cent cut across all sectors, globally, except agriculture – including, therefore, the electricity and heating sectors, manufacturing, construction, transport, industrial processes, forestry and waste. Such a scale of cuts, implemented globally within only 10 years, is likely to lie at the boundary of feasibility with foreseen technologies. For comparison, a 10 per cent annual rate of reduction is equivalent to a 65 per cent reduction in global emissions over 10 years. Setting a lower ambition (i.e. smaller emissions reductions) for a target in 2020, and relying on achieving such high rates of reductions subsequently, is a high-risk strategy.

Finally, as well as targets for global annual emissions in 2020 and 2050, the date and height of the peak in emissions are also determinants of the economic costs and feasibility of paths. For example, in our scenario where emissions were 54 Gt CO_2e in 2020, but did not peak until 2025 (at 57 Gt CO_2e), we found that emissions must be reduced at an average rate of more than 8.5 per cent per year between 2025 and 2050, to a very low level of 6 Gt CO_2e in 2050, to achieve the 2°C climate goal. As the previous discussion indicated, we have judged such a scenario to lie at the boundary of feasibility. In addition to the rapid rate of reductions, the level of emissions in 2050 would have to be below what we might expect from agriculture alone. We conclude therefore, that a responsible emissions path for the 2°C climate goal would peak before 2020.

3.5.2 Narrowing the envelope window in 2020: 40 – 48 Gt CO_2e

The discussion in previous sections supports the setting of the edges of the envelope window in 2020 at 40 and 54 Gt CO_2e on the grounds of feasibility. On the basis of economic costs and risk, it is possible to narrow the envelope window in 2020 to the bottom part of the range, extending between around 40 and 48 Gt CO_2e. This would also narrow the envelope window in 2050 to lie between about 14 to 17 Gt CO_2e in 2050. These windows imply that global emissions should peak before 2020, with average emission reductions of between 3 and 4 per cent per year between 2020 and 2050. The reasons for lowering the upper bound of the 2020 window include:

- The research reported in this paper and elsewhere has demonstrated clear benefits from early action to reduce global emissions, compared with delayed action. For example, den Elzen *et al*. (2007) demonstrated that early-abatement paths reap benefits from encouraging more induced technical progress early on and avoiding the need for very sharp annual reductions in emissions along the way. In addition, there are many 'low-hanging fruit', such as improvements in energy efficiency, that can provide significant, cheap emissions reductions quickly, as well as co-benefits, if market failures are tackled. There is no reason not to deal with these market failures as soon as possible in the near term to secure early emissions reductions. For example, McKinsey & Company (2009) demonstrated the possible scope for low- or negative-cost mitigation if various market failures affecting the use of energy are tackled so as to improve energy efficiency significantly. McKinsey & Company (2009) identified potential reductions in annual emissions in industry, agriculture and the home of more than 10 Gt CO_2e per year by 2030 with negative costs.
- Part 2 demonstrated that paths lying above about 48 Gt CO_2e in 2020 only give a reasonable chance of achieving the 2°C climate goal if we assume relatively high aerosol emissions over the next 100 years. Given the health and environmental benefits of lower aerosol emissions, and the current policy trend towards stronger air pollution regulation, we have concluded that adopting a target that relies upon higher aerosol emissions is not a responsible option. Placing the upper boundary to the envelope window in 2020 at 48 Gt CO_2e is supported by many published studies to date (e.g. the review by den Elzen and Hohne, 2008).
- Paths towards the upper end of the envelope window in 2020 rely on overshooting atmospheric concentrations of greenhouse gases and then declining rapidly. This would require rapid reductions in emissions to very low levels. The feasibility of such scenarios is not proven in terms of science, economics or technological feasibility. In addition, Part 2 showed that paths with lower ambition in 2020 are associated with more rapid rates of temperature change and, therefore, potentially more damage and risk of irreversible impacts.
- Finally, the uncertainties in the emissions targets for 2050 that are highlighted in Part 2, as well as the uncertainty about whether the 2°C climate goal itself is the right one (given that we are still learning about the science and economics of climate change), suggest the need to maintain flexibility in emissions paths in the near term. Aiming towards the upper portion of the envelope window in 2020 reduces flexibility; for example, if after reaching 54 Gt CO_2e in 2020, we found that the carbon cycle was more sensitive to anthropogenic emissions than suggested by the central case, and so annual emissions needed to be reduced to 5 Gt CO_2e in 2050 to avert very damaging impacts, then the rate of reduction would have to be more than 7.5 per cent per year between 2020 and 2050. At the lower end of the 2020 envelope window, there is more flexibility; we would be in a better place to start with in terms of emissions, and would be able to reap the benefits from the induced technological progress that was already achieved.

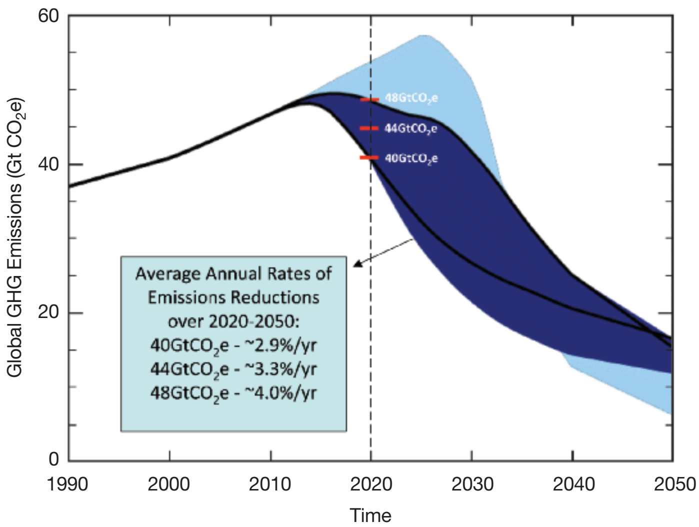

Figure 3.1: Simulated emissions paths that have a 50 per cent chance of limiting warming no more than 2°C above pre-industrial levels (from Part 2). The light blue region shows emissions paths that meet the climate goal under the higher aerosol emissions scenario and the dark blue region shows paths that meet the goal even with the lower aerosol emission scenario.

3.6 Enabling an emissions path for the 2°C climate goal: lessons learned for policy-making

Recent analyses have made it clear that the challenge of keeping below the 2°C ceiling will be great, but they have also suggested what steps policy-makers should take to achieve strong emissions reductions and minimise costs. First and foremost, early action by as many countries as possible is desirable, for the reasons discussed in previous sections. Efforts to reduce emissions relative to 'business as usual' are needed worldwide to keep the total costs down; financial flows from richer to poorer countries will be required to ensure that the costs of these efforts are equitably distributed. Early action will not be reflected in sharp emissions reductions immediately in all sectors of the economy, because of the time it will take to build confidence in the policy framework among firms and households, for the capital stock to be transformed, and for new technologies to become cost effective. However, some 'quick wins' are likely to be achieved if policies rapidly move to correct the market failures currently standing in the way of exploiting 'negative cost' abatement opportunities. McKinsey & Company (2009) identified negative-cost abatement opportunities of nearly 3 Gt CO_2e which could be achieved annually by as soon as 2015. Many market failures do not require investment with long gestation periods to correct them – rather, they require that public authorities provide information, set appropriate financial incentives and provide seed-corn investment to demonstrate the effectiveness of the policy approach. Changing consumption and input purchase patterns in response to carbon pricing can also have significant effects relatively quickly. Later on, emissions reductions are likely to accelerate at the times when key low-carbon technologies become sufficiently productive to compete with existing high-carbon technologies, so that whole industry sectors decarbonise as soon as their capital stock is renewed. That will require significant extra investment, especially in the energy sector, each year.

Hence, with good policies, one would expect to see a step downwards in emissions relative to 'business as usual' soon after the policy framework is put in place. There would then be further steps as the conditions become satisfied for whole industrial sectors to go low-carbon. The 'step' impact of introducing climate change policies has been illustrated in some modelling exercises, such as that by Goettle and Fawcett (2009), although it has not been incorporated by all modellers. Some models that analysed cap-and-trade climate change regimes, and allowed banking and borrowing, have suggested that companies will reduce emissions faster than a linear reduction schedule starting from existing levels would suggest, so that they can bank emissions quotas for future use (e.g. Ross *et al*., 2009, who envisaged for the USA a sharp reduction in greenhouse gas emissions within the first five years of policy, especially if offsets and set-asides are included). In other words, firms find that they can abate earlier and do so, because it is in their interests.

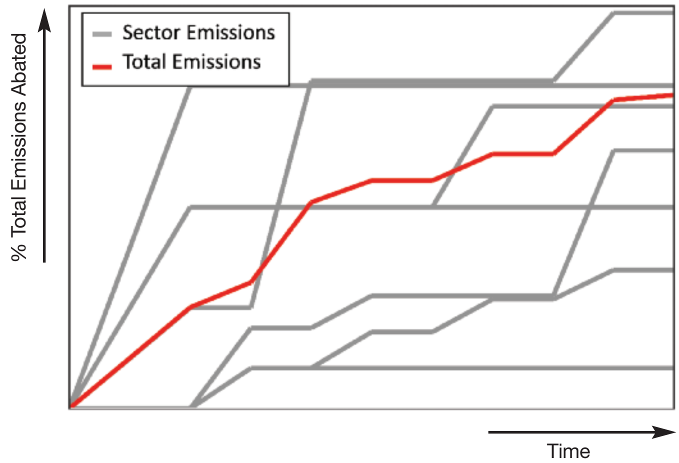

Figure 3.2: Schematic diagram illustrating the possible path of total emissions (global or national) and its relationship to sectoral emissions paths. Key points to note are that the majority of sectors will very probably show initial rapid reductions in emissions as they exploit 'low-hanging fruit'. After this we expect to see a pattern of plateaux and low emissions reductions as policies come into effect and technologies are developed, followed by periods of rapid sectoral emissions reductions as new technologies are implemented. Overall, this could lead to total emissions reducing quickly initially, followed by a period of sustained gradual declines in emissions.

The prospect of a step reduction in emissions soon after adoption of strong policies implies that the most cost-effective way of trying to keep a global temperature increase below 2°C is with an early peak in emissions.

3.7 A desirable global policy framework

This discussion of economic costs and feasibility has strong implications for the form of a desirable global policy framework:

- It would be best for all countries to start taking action now; there will be few benefits from delay for any region.[29] Not all the effects of tough policies will be seen immediately in emissions reductions, but a step improvement in the early years should be possible if the whole range of relevant market failures is tackled.
- Keeping costs down requires the application of policies across all greenhouse gases and all sectors as well as all countries. These policies need not utilise the same instruments but they do need to be broadly equivalent in their intensity.
- Cost-effectiveness requires a common effective (implicit or explicit) carbon price prevailing as widely as possible. This is one diagnostic of whether policies that differ in design and implementation are broadly equivalent in their effect.
- Near-term annual emissions targets should be used as another diagnostic, to help monitor whether collectively countries are moving towards their long-term goal at broadly the right pace and to enable civil society to hold policy-makers to account.
- Cost-effective mitigation will generally entail an early peak in annual emissions, especially if policy-makers' discount rates are low.
- An ambitious long-term goal for climate change policies makes it more imperative to overcome a range of well-known market failures, particularly in research, development and early deployment. Early deployment of low-carbon technologies is needed globally, both to avoid locking-in the use of high-carbon technologies into new long-lived plant and equipment, and to deliver learning and experience. That will require policies to promote the diffusion of knowledge across developed and developing countries alike.
- The international community needs to keep climate change policy targets under review, amending them as necessary in the light of the developing scientific and economic evidence about risks, impacts, technologies and costs of policy. With quantitative targets for emissions reductions, carbon prices (implicit or explicit) would be a useful diagnostic to assess whether reductions are proving more or less easy than anticipated. Variations in carbon prices across countries would provide a diagnostic of the cost effectiveness of global policies.

[29] Delay by some regions raises the possibility of 'carbon leakage', not least through land-use policies in the late adopters, weakening climate change policy overall and distorting the location of production in a costly way.

Annex 1 Our approach and its implications for our conclusions

This Annex describes our methodology and gives further details about the uncertainties in the targets for 2020 and 2050, drawing on the assumptions and findings of similar studies. It is of prime importance to understand the uncertainties in the targets due to the approach that has been adopted. We have found in this study that even slight differences in the specifications in the climate modelling, the definition of the temperature constraint (i.e. our climate goal) and the emissions scenarios, can have a significant effect on whether the goal is met or not. This explains much of the disagreement between studies.

It is impossible to define success or failure of a temperature-based target without taking into account some model dependence; this is inherent in the use of such a target, whatever the approach, and is a challenge for the UNFCCC negotiations in terms of defining an objective long-term goal for climate change mitigation. Our approach has been to use information and modelling that we assess to be the best available, along with the most plausible scenarios; to be transparent about these assumptions; and, to give as a minimum, an order of scale for the uncertainties in the targets.

A.1.1 The approach

A.1.1.1 Development of emissions paths

The envelope of emissions paths was determined by analysing a set of idealised paths generated using the SiMCaP EQW model (Meinshausen *et al*., 2005, 2006). An advantage of the SiMCaP EQW model is that it incorporates an emissions baseline that is aligned with observations and recent projections of the IEA (2008, 2009[30]). This is important, as future emissions targets are sensitive to the baseline emissions assumption. In the SiMCaP EQW model, emissions paths are generated to meet a set of specified criteria using an iterative method. The criteria used in this study are: (i) the long-term goal (i.e. a temperature or greenhouse gas concentration target); (ii) the dates of departures of emissions from 'business as usual' of four country groups; and (iii) the maximum allowable annual reductions in global emissions. The SiMCaP model also provides climate projections for each emissions path from a simplified climate model; in this study, we used these climate projections for high-level filtering only. We initially generated a set of about 100 emissions paths by varying each of the criteria within reasonable limits (e.g. exploring temperature targets around the 2°C goal and targets for greenhouse gases around the range between 400 and 550 ppm CO_2e, with departure dates varying between about 2010 and 2060, and maximum reduction rates of up to 50 ppm per cent per year). An initial filtering was then applied, which removed any paths that had: (i) a global emissions peak earlier than 2015 and (ii) global mean temperature estimates exceeding around 2.4°C at any time. Criterion (i) reflects our assessment that, given current circumstances, it seems very unlikely that global emissions will peak before 2015. From this set of emissions paths, we selected a smaller representative set of 20 paths for which we assessed climate outcomes in more detail.

The design of the idealised emissions paths allowed us to explore the sensitivity of targets for 2020 and 2050 to the shape of the path; in particular, the date of the emissions peak and the rate of emissions reductions over time. However, the experimental design did not allow us explicitly to explore uncertainties related to other aspects, such as the emissions baseline, the rates of abatement of different greenhouse gases and the emissions floors. In this study, these aspects were set to what we assess to be the most plausible scenarios, details of which are given in the supplementary materials. An important aspect of scenario uncertainty that we have quantified explicitly is the path of future anthropogenic aerosol emissions. Overall, aerosols cool the climate and, therefore, scenarios with higher aerosol emissions require less stringent emissions targets. To incorporate this uncertainty, we generated and applied two scenarios of future aerosol emissions: an 'upper' and 'lower' scenario. The upper aerosol scenario was derived from the IPCC SRES B1 scenario (Nakićenović *et al*., 2000), which is at the medium-high end of the current range of aerosol projections (Fisher *et al*., 2007). The lower aerosol scenario was taken from the SiMCaP EQW model and is at the low end of current projections. These scenarios were not designed to span the entire space of all possible outcomes, but should be interpreted as equally plausible scenarios. Further details about the assumptions for emissions scenarios are given in the supplementary materials.

[30] The reference scenario from the IEA's World Energy Outlook 2008 estimates greenhouse gas emissions of approximately 48 Gt CO_2e in 2010 and 55 Gt CO_2e in 2020 (IEA, 2008). The IEA's reference scenario can be considered a 'business as usual' scenario from today; it includes policies enacted or adopted (though not necessarily fully implemented) to date, but not policies under consideration (e.g. no 'targets' that are not backed up by commensurate action). The 2009 estimates are around 2 Gt CO_2e lower in 2020, mainly due to the effects of the global recession (IEA, 2009). This is roughly consistent with the baseline emissions in this study: 47 Gt CO_2e in 2010 and 54 Gt CO_2e in 2020.

A.1.1.2 Assessment of climate outcomes

The assessment of climate outcomes was undertaken in partnership with the Met Office Hadley Centre (MOHC) using its tuning of the MAGICC model (Lowe *et al*., 2009). The MAGICC model is a simple climate model; an upwelling diffusion energy-balance model connected to carbon and other gas cycle models (Wigley and Raper, 2001), which can be tuned to represent the output of more complex models. The advantage of the MAGICC model for this study is that it allows one to explore uncertainties in climate outcomes stemming from uncertainties in key input parameters, for example, the climate sensitivity, ocean diffusivity and carbon cycle feedbacks. The model is computationally fast, so suitable for running large numbers of simulations in order to explore uncertainties. Further details on the climate assumptions of the model are given in the supplementary materials.

MAGICC provides an important tool for understanding uncertainty, and is therefore an advance on a single-model-based approach. However, in any model-based approach, some dependency is incorporated and unavoidable due to choices of model, parameterisations, etc.. The Appendix includes an assessment of the key assumptions in the method about climate parameters, such as the climate sensitivity. The parameters were chosen such that they are consistent with the findings of the IPCC Fourth Assessment Report (2007). As such, the climate assumptions were likely to indicate more stringent cuts in emissions than suggested by older studies (as IPCC (2007) increased estimates of the sensitivity of the Earth's system to human action across a number of variables, including the climate sensitivity). Model structural uncertainty (i.e. inter-model differences) and systematic uncertainties are not discussed in detail here. Simple models, like MAGICC, do not explicitly represent many of the processes that are included in contemporary Earth System Models. They have, however, demonstrated some skill at reproducing the response of global average temperature to anthropogenic emissions. A lower bound on structural uncertainty is developed through comparison with multi-model results from IPCC (2007). In addition to this, there are systematic biases across all models due to, for example, missing processes like methane feedbacks. Quantifying this additional uncertainty is beyond the scope of this study; however it does mean that any uncertainty estimates cited in this policy brief are lower bounds to the true values.

The climate model version used in this study is the same as that used in the MOHC-led AVOID research programme. This programme will shortly produce further analyses of emissions paths with the same assumptions about climate, but different assumptions about experimental design and emissions scenarios, providing a useful comparison to assist further understanding of the uncertainties.

A.1.1.3 Definition of our climate goal

We found that our analysis was sensitive to the definition of the climate science constraint, i.e. our 2°C goal. Here, for an emissions path to meet the climate goal, it must be consistent with a rise in global mean temperature that is equal or less than 2°C above pre-industrial level, with a probability of at least a 50 per cent (based on our climate model assumptions) between now and 2200, where: pre-industrial level is defined as the global mean temperature averaged over the period 1861-1890 and a rise of 'equal or less than' 2°C is defined to one decimal place (i.e. less than 2.05). The emissions path must also be consistent with a probability of no more than 10 per cent of a rise of more than 3°C, and a probability of less than 5 per cent of a rise of more than 4°C. We have concluded from this that for a temperature-based goal to be workable within a climate agreement, definitions must be laid out clearly. Perhaps surprisingly, the subtle variations in definitions can correspond to differences in emissions targets of several gigatonnes.

A.1.2 Assessing the implications of uncertainty for the conclusions

There are two main types of uncertainties that must be considered. The first is uncertainty in emissions scenarios. For example, differences in scenarios of emissions growth over the coming years have a significant bearing on the magnitude of reductions in the longer term; more rapid growth now means that stronger cuts would need to be made later on. The second type of uncertainty arises from the science; that is, the response of the Earth system to anthropogenic emissions. The assumptions and uncertainties in this study are described in detail in the supplementary materials (available at http://www.lse.ac.uk/grantham). Our treatment of these uncertainties has implications for our findings and this has been taken into account in drawing the conclusions. In this section, we consider these uncertainties and their implications by comparing our findings with those of other studies. We then use this information, plus our own envelope of emissions paths, to estimate the scale of uncertainties in emissions targets.

A.1.2.1 Comparison with other recent studies

It is difficult to compare directly the findings of this study with previous work as no other studies to date have attempted to map the full envelope of emissions paths, in terms of both emissions in 2020 and peak dates, that are consistent with our climate goal. The closest in relevance was Meinshausen *et al*. (2009), which adopted the similar approach of analysing an ensemble of emissions paths using a probabilistic simple climate model. Both studies used a similar model framework, but had different parameter settings and experimental design. Meinshausen *et al*. (2009) suggested that, to give a reasonable chance of keeping temperatures from rising by more than 2°C, global annual emissions would need to be below 50 Gt CO_2e in 2020, and around 20 Gt CO_2e in 2050. The authors suggested that emissions in 2020 of 40 or 50 Gt CO_2e would result in a probability of meeting the 2°C goal of 63 per cent (with a range of 44 to 81 per cent) or 26 per cent (with a range of 13 to 47 per cent), respectively. Based on our climate assumptions, we would expect our probability estimates to be lower than those of the central estimate of Meinshausen *et al*. (2009), but well within their wider range. We suggest that the findings of Meinshausen *et al*. (2009) for emissions in 2020 are roughly in line with our lower aerosol scenario, in which we estimate a range of 40 to 48 Gt CO_2e [31] for emissions in 2020. Our estimate for emissions in 2050 appears lower than that of Meinshausen *et al*. (2009); our 2050 window for the lower aerosol scenario was 14 to 17 Gt CO_2e, while Meinshausen *et al*. (2009) suggested that emissions of up to 20 Gt CO_2e in 2050 would result in a probability of only 32 per cent (with a range of 15 to 49 per cent) of a rise of more than 2°C. We suggest that this difference is due to uncertainty in the current understanding of the science. We assumed a slightly higher climate sensitivity and sensitivity for the carbon cycle than Meinshausen *et al*. (2009), although we were still consistent with the current consensus.

The estimated cumulative totals for Kyoto greenhouse gas emissions that would result in a reasonable chance of limiting warming to no more 2°C were also roughly consistent between the two studies. For example, Annex 2 shows that paths in this study tend to be associated with cumulative emissions between 2000 and 2050 of around 1500 to 1900 Gt CO_2e for the upper aerosol scenario, or less than 1750 Gt CO_2e for the lower aerosol assumption. Meinshausen *et al*. (2009) found that cumulative emissions of 1500 Gt CO_2e (with their lower end aerosol assumption) resulted in a probability of between a 57 and 90 per cent of a rise of less than 2°C, while 2000 Gt CO_2e led to a probability of 30 to 71 per cent (where we would expect our climate sensitivity assumption to lead to a probability at the lower end of range estimated by Meinshausen *et al*., 2009). We note also that our finding of maximum cumulative emissions of 2100 Gt CO_2e between 2000 and 2100 under the lower aerosol assumption (or 2300 Gt CO_2e under the upper aerosol assumption) is roughly in line with the 2100 Gt CO_2 (only) indicated by Allan *et al*. (2009).

A comparison of our results with the preliminary findings of the AVOID programme (Lowe, pers. comm.) provides further evidence that our window for global annual emissions in 2020 that are consistent with the 2°C goal is robust to within a few gigatonnes under different, but plausible, assumptions about baseline emissions and individual options for the abatement of greenhouse gas emissions. However, comparing this study with that of Meinshausen *et al*. (2009) and the AVOID programme, shows the apparent sensitivity to assumptions about aerosols; lower levels of aerosol emissions require much lower emissions of greenhouse gases in 2020 to achieve the same climate goal. Preliminary findings from the AVOID programme also suggest that the target level in 2050 is more sensitive to assumptions, particularly about the emissions scenario and the climate model.

Other studies in the peer-reviewed literature have tended to generate a much smaller number of emissions paths and have explored a smaller range of options. However, a comparison with individual paths in this study can still provide useful information on uncertainties. These studies provide support for our conclusion that the window for global annual emissions in 2020 is well-constrained. However, there is more variability in the estimates for 2050, due to uncertainties in the science, the definition of the long-term goal, and the assumptions about scenarios (particularly different assumptions about baselines and relative rates of abatement of emissions of different greenhouse gases). For example, den Elzen *et al*. (2007) found that global annual emissions would need to lie within the range of approximately 37 to 46 Gt CO_2e in 2020, and 15 to 28 Gt CO_2e in 2050, to stabilise concentrations at 450 ppm CO_2e (peaking at 510 ppm CO_2e). They stated that such scenarios would give a better than evens chance of keeping temperatures from rising 2°C or more above pre-industrial levels. This study used similar assumptions about aerosol emissions, but explored different baseline scenarios. The range in 2020 is quite similar, although global annual emissions in den Elzen *et al*. (2007) were not as high as the paths were assumed to peak in around 2015. Their range of emissions in 2050 appear higher than in our study. We

[31] This is unsurprising, given that the aerosol assumptions are not independent. Our lower aerosol assumption comes from an earlier version of the Meinshausen *et al*. (2009) model.

suggest that the main reason for this is again the difference in the climate sensitivity and carbon cycle assumptions. For example, den Elzen *et al*. (2007) used the 'IPCC 2001 lognormal PDF' of climate sensitivity (Wigley and Raper, 2001), which is more optimistic (i.e. assumes a lower sensitivity) than the Murphy *et al*. (2004) distribution used in our study. This means that if den Elzen *et al*. (2007) had employed our climate model assumptions, their paths would have exceeded 2°C.

den Elzen and Höhne (2008) reviewed the findings of 11 studies between 2001 and 2008 that assessed the emissions reductions required for atmospheric levels of greenhouse gases to stabilise at around 450 ppm CO_2e. A subset of these studies was used to inform the IPCC (2007) assessment of Annex I and non-Annex I commitments for different long-term goals (Gupta *et al*., 2007). Across these 11 studies, the range for global emissions (excluding LULUCF emissions[32]) in 2020 was 10 to 30 per cent above 1990 levels. This equates to about 41 to 48 Gt CO_2e[33]. For 2050, the range was 35 to 80 per cent below 1990 levels, or roughly 7 to 24 Gt CO_2e (one study suggested 30 Gt CO_2e). Some of the overlap in the ranges for 2020 between this study and den Elzen and Höhne (2008) is likely to be a coincidence i.e. the ranges are the same, but for different reasons. For example, den Elzen and Höhne (2008) suggested that some of the earlier studies included unrealistically low baseline emissions[34], resulting in estimates for emissions in 2020 that were also too low. However, more recent studies reported in den Elzen and Höhne (2008) published since IPCC (2007) provide support for these ranges, though again usually for different reasons. We point out that the range for emissions in 2050 appears higher across the 11 studies because those studies have used more optimistic (i.e. lower) assumptions about climate sensitivity and the strength of carbon cycle feedbacks.

The technical emissions path analysis (Smith *et al*., 2008) of the 2008 report of the UK Committee on Climate Change (CCC, 2008) used a similar climate modelling approach to that employed in this study, but with different assumptions about baseline emissions and future environmental policies: future aerosol emissions and the balance between carbon dioxide and methane abatement over time. Their future policy assumptions would tend to lead to less stringent emissions reductions required in 2050. Only one of their emissions paths led to a probability of close to 50 per cent of limiting warming to no more than 2°C above pre-industrial levels – the "2014:3%low+" path. This path resulted in a 49 per cent chance in 2100 and a 47 per cent chance in 2200 of exceeding a rise of 2°C. That path had emissions of 44 Gt CO_2e in 2020 and 20 Gt CO_2e in 2050. This further confirms our conclusion that our estimates of emissions target options for 2020 are robust under different assumptions, but the targets for 2050 are more sensitive to climate modelling assumptions, and also assumptions about future environmental policy.

A.1.2.2 Quantifying uncertainties around targets

After comparing our findings with those of other studies, we have concluded that the target level for 2020 is relatively robust to within a few gigatonnes under plausible scenarios, except for a strong sensitivity to aerosols. Under a lower aerosol assumption, the upper boundary of the emissions window appears to be around 6 Gt CO_2e lower in 2020 than for the higher aerosol scenario. The lower sensitivity of the targets to other assumptions about climate and emissions in 2020 was probably due to the fact that they were set only 10 years from the present[35].

We have shown that the uncertainties appear to be much larger around the target for 2050. After comparison with the preliminary results from the AVOID programme and Smith *et al*. (2008), we have concluded that for a fixed target in 2020 (within our envelope), the uncertainties associated with the emissions alone (in particular, differences in the plausible assumptions about aerosol emissions, about the relative rates of abatement for different greenhouse gases, and about the emissions floor) were of the order of ±4 Gt CO_2e for the target in 2050. This estimate is consistent with what would be expected from the sensitivity of the results in this study to different aerosol scenarios. For example, Table 2.1 shows that the differences in temperature in 2100 between the two aerosol scenarios is roughly 0.1°C; by comparing paths with similar emissions in 2020 (e.g. paths 1 and 2), 0.1°C appears to be equivalent to a difference in emissions in 2050 of roughly ±2.5 Gt CO_2e.

[32] Land-use, land-use change and forestry.

[33] Absolute levels for all emissions are based on percentage change estimates for emissions excluding LULUCF, which introduced an error.

[34] For example, some earlier studies assumed that the USA met its targets under the Kyoto Protocol and did not take into account the rapid growth in emissions from Asia over the past decade (den Elzen and Höhne, 2008).

[35] Most studies have used plausible emissions scenarios and climate assumptions that are close to the consensus position; thus differences between studies have been small. With more extreme scenarios, or where climate assumptions are towards the edges of their distributions, this might not be the case. For example, stronger cuts will be required if the sensitivity of the Earth's system to emissions is much higher than currently estimated.

Much larger uncertainties in the targets for 2050 arise from the climate assumptions (i.e. the uncertainties in the response of the climate to anthropogenic emissions). Our targets for 2050 are lower than most of those suggested by other recent studies, mainly because of differences in climate model assumptions (particularly the climate sensitivity and carbon cycle feedbacks). The climate model assumptions in this study were generally based on more recent work than those in past studies. However, the uncertainty around the targets that was due to the climate assumptions is real (i.e. the science is still uncertain). A full assessment is beyond the scope of this study, but we can draw three main conclusions about the scale of the uncertainties due to (i) parameter uncertainties within the model and (ii) structural uncertainties (i.e. those caused by, for example, missing processes in the model):

- A comparison with Meinshausen *et al*. (2009), which used a similar model but different within-model parameter assumptions, suggests that there is a range of uncertainty of around 4 Gt CO_2e in 2050, which is due mainly to our different assumptions about the distribution (e.g. the median and likely range) of climate sensitivity and carbon cycle feedbacks.
- The estimates for emissions targets suggested by both this study and Meinshausen *et al*. (2009) are determined mainly by the median climate sensitivity and carbon cycle feedbacks. Across the full distribution of possible climate sensitivities and carbon cycle feedbacks, the implied uncertainty in emissions targets is much greater. For example, for a climate sensitivity at the upper end of the assumed distribution, emissions reductions targets would need to be much greater to achieve the same climate goal. This can be explored by looking at the range of temperature projections that are generated by the model. Our study estimated that the 10th percentile for temperatures in 2100 for each emissions path was approximately 0.5˚C lower than the median (50th percentile) value. The 90th percentile for each path was about 0.9°C higher than the median. By comparing the median temperature projections for different paths, a rough estimate of the range of uncertainties could be determined. For example, the annual emissions in 2050 for paths 1 and 2 differed by 5 Gt CO_2e, but only by 0.1°C in terms of median temperature projections for 2100. Paths 8 and 9 differed by 10 Gt CO_2e in terms of annual emissions in 2050, and by 0.3°C for temperature projections in 2100 temperature. From this, we could have concluded that the range around the median temperature of -0.5 to +0.9°C (defined by the 10th and 90th percentile) corresponds to a large uncertainty in emissions. However, there are non-linear effects that would prevent such a direct comparison.
- The two preceding conclusions relate only to parameter uncertainty. Taking structural uncertainty into account as well would lead to even higher estimates of uncertainty. We can estimate the scale of 'between-model' uncertainties by comparing the temperature projections from this study with those from the range of models assessed in IPCC (2007). The temperature projections for the SRES B1 scenario lie closest to our emissions paths (giving a 'best estimate' warming of 1.8°C above pre-industrial levels), and provide the best comparison. IPCC (2007) estimated that the likely (i.e. a chance of 66–90 per cent) range of warming for this scenario was 1.1 to 2.9°C, or -0.7 to +1.1°C compared with the 'best estimate' of 1.8°C. This suggests that our single-model approach has underestimated the range of uncertainty in temperature, compared with that given by a multi-model approach, by a few tenths of a degree. This implies an larger level of uncertainty around the estimates for emissions in 2050. One further aspect that can not be assessed here is the broader structural uncertainty caused by the limitations of our current suite of climate models, particularly missing processes, such as methane feedbacks, which may have important implications for emissions targets.

From this limited assessment, we conclude that the uncertainty around our estimates for 2050 targets is of the order of at least ±5 to 10 Gt CO_2e. The scale of the uncertainties related to the emissions paths and the science, and the risks associated with them, highlight the need to reassess targets regularly as new evidence emerges, and to set targets for 2020 that would allow a more demanding climate goal to be achieved by adjusting the path for emissions in subsequent years.

Annex 2 Key information for 20 emissions paths

Path Number	Global Greenhouse Gas Emissions (Gt CO_2e)								Average Annual Rates of Emissions Reductions		Global Average Temperature Projections (relative to pre-industrial) based on the 'Upper' Aerosol Scenario					Global Average Temperature Projections (relative to pre-industrial) based on the 'Lower' Aerosol Scenario				
	Emissions in 2020 (& percentage change relative to 1990 levels)		Emissions in 2050 (& percentage change relative to 1990 levels)		Peak Emissions		Cumulative Emissions		Near -term: 2015-2020	Medium -term: 2020-2050	Median Warming Estimate		Estimated Probability of Exceeding Temperature Level in 2100*			Median Warming Estimate		Estimated Probability of Exceeding Temperature Level in 2100*		
					Date	Scale	2000-2050	2000-2100			2100	2200	2°C	3°C	4°C	2100	2200	2°C	3°C	4°C
1	40	8%	17	-54%	2014	48	1635	2079	-3.5%	-2.9%	1.9	1.8	45%	5%	<5%	2.0	1.8	50%	10%	<5%
2	40	10%	12	-68%	2014	48	1487	1908	-3.5%	-4.0%	1.8	1.7	35%	5%	<5%	1.9	1.8	45%	5%	<5%
3	41	10%	17	-55%	2014	48	1631	2160	-3.2%	-3.0%	2.0	1.9	50%	5%	<5%	2.1	2.0	55%	10%	<5%
4	44	19%	14	-62%	2015	50	1644	2055	-2.3%	-3.7%	1.9	1.8	45%	5%	<5%	2.0	1.8	50%	5%	<5%
5	44	19%	16	-57%	2015	50	1698	2127	-2.3%	-3.3%	1.9	1.8	45%	5%	<5%	2.0	1.9	50%	10%	<5%
6	44	19%	16	-57%	2015	50	1698	2173	-2.3%	-3.3%	2.0	1.9	50%	5%	<5%	2.1	1.9	55%	10%	<5%
7	45	21%	12	-68%	2015	49	1752	2148	-1.6%	-4.3%	2.0	1.9	50%	5%	<5%	2.0	1.9	50%	10%	<5%
8	47	26%	24	-34%	2016	49	1907	2661	-1.0%	-2.1%	2.2	2.1	65%	10%	<5%	2.3	2.2	75%	15%	<5%
9	48	30%	14	-62%	2016	49	1715	2105	-0.5%	-4.0%	1.9	1.8	45%	5%	<5%	2.0	1.9	50%	5%	<5%
10	49	31%	15	-58%	2019	49	1897	2324	-0.3%	-3.8%	2.0	1.9	55%	10%	<5%	2.1	2.0	60%	10%	<5%
11	50	34%	12	-68%	2020	50	1834	2230	0.4%	-4.6%	2.0	1.9	50%	5%	<5%	2.1	1.9	55%	10%	<5%
12	50	37%	13	-65%	2018	51	1853	2238	0.1%	-4.4%	2.0	1.9	50%	10%	<5%	2.1	1.9	55%	10%	<5%
13	52	40%	13	-65%	2019	52	1816	2223	0.5%	-4.5%	2.0	1.9	50%	5%	<5%	2.1	2.0	55%	10%	<5%
14	52	40%	13	-65%	2019	52	1816	2223	0.5%	-4.5%	2.0	1.9	50%	5%	<5%	2.1	2.0	55%	10%	<5%
15	52	40%	21	-44%	2019	51	2013	2684	0.5%	-3.0%	2.2	2.3	65%	10%	<5%	2.3	2.4	75%	15%	<5%
16	54	45%	11	-70%	2023	55	1897	2266	1.4%	-5.1%	2.0	1.9	50%	10%	<5%	2.1	1.9	55%	10%	<5%
17	54	45%	17	-55%	2020	54	2058	2494	1.4%	-3.8%	2.1	2.0	60%	10%	<5%	2.2	2.1	65%	15%	<5%
18	54	45%	6	-83%	2025	57	1869	2218	1.4%	-6.9%	2.0	1.9	50%	10%	<5%	2.1	1.9	55%	10%	<5%
19	54	45%	12	-68%	2020	54	2102	2462	1.4%	-4.9%	2.1	2.0	60%	10%	<5%	2.2	2.1	65%	15%	<5%
20	54	45%	13	-65%	2020	54	2213	2579	1.4%	-4.6%	2.2	2.1	65%	10%	<5%	2.2	2.1	65%	15%	<5%

*Probability estimates are rounded to the nearest 5% to reflect uncertainties. Probabilities less than 5% are all indicated as '<5%' as tails of the distributions have the greatest uncertainty.

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