Executive Summary

The scientific evidence is now overwhelming: climate change presents very serious global risks, and it demands an urgent global response.

This independent Review was commissioned by the Chancellor of the Exchequer, reporting to both the Chancellor and to the Prime Minister, as a contribution to assessing the evidence and building understanding of the economics of climate change.

The Review first examines the evidence on the economic impacts of climate change itself, and explores the economics of stabilising greenhouse gases in the atmosphere. The second half of the Review considers the complex policy challenges involved in managing the transition to a low-carbon economy and in ensuring that societies can adapt to the consequences of climate change that can no longer be avoided.

The Review takes an international perspective. Climate change is global in its causes and consequences, and international collective action will be critical in driving an effective, efficient and equitable response on the scale required. This response will require deeper international co-operation in many areas - most notably in creating price signals and markets for carbon, spurring technology research, development and deployment, and promoting adaptation, particularly for developing countries.

Climate change presents a unique challenge for economics: it is the greatest and widest-ranging market failure ever seen. The economic analysis must therefore be global, deal with long time horizons, have the economics of risk and uncertainty at centre stage, and examine the possibility of major, non-marginal change. To meet these requirements, the Review draws on ideas and techniques from most of the important areas of economics, including many recent advances.

The benefits of strong, early action on climate change outweigh the costs

The effects of our actions now on future changes in the climate have long lead times. What we do now can have only a limited effect on the climate over the next 40 or 50 years. On the other hand what we do in the next 10 or 20 years can have a profound effect on the climate in the second half of this century and in the next.

No-one can predict the consequences of climate change with complete certainty; but we now know enough to understand the risks. Mitigation - taking strong action to reduce emissions - must be viewed as an investment, a cost incurred now and in the coming few decades to avoid the risks of very severe consequences in the future. If these investments are made wisely, the costs will be manageable, and there will be a wide range of opportunities for growth and development along the way. For this to work well, policy must promote sound market signals, overcome market failures and have equity and risk mitigation at its core. That essentially is the conceptual framework of this Review.

The Review considers the economic costs of the impacts of climate change, and the costs and benefits of action to reduce the emissions of greenhouse gases (GHGs) that cause it, in three different ways:

- Using disaggregated techniques, in other words considering the physical impacts of climate change on the economy, on human life and on the environment, and examining the resource costs of different technologies and strategies to reduce greenhouse gas emissions;

- Using economic models, including integrated assessment models that estimate the economic impacts of climate change, and macro-economic models that represent the costs and effects of the transition to low-carbon energy systems for the economy as a whole;

- Using comparisons of the current level and future trajectories of the 'social cost of carbon' (the cost of impacts associated with an additional unit of greenhouse gas emissions) with the marginal abatement cost (the costs associated with incremental reductions in units of emissions).

From all of these perspectives, the evidence gathered by the Review leads to a simple conclusion: the benefits of strong, early action considerably outweigh the costs.

The evidence shows that ignoring climate change will eventually damage economic growth. Our actions over the coming few decades could create risks of major disruption to economic and social activity, later in this century and in the next, on a scale similar to those associated with the great wars and the economic depression of the first half of the 20th century. And it will be difficult or impossible to reverse these changes. Tackling climate change is the pro-growth strategy for the longer term, and it can be done in a way that does not cap the aspirations for growth of rich or poor countries. The earlier effective action is taken, the less costly it will be.

At the same time, given that climate change is happening, measures to help people adapt to it are essential. And the less mitigation we do now, the greater the difficulty of continuing to adapt in future.

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The first half of the Review considers how the evidence on the economic impacts of climate change, and on the costs and benefits of action to reduce greenhouse gas emissions, relates to the conceptual framework described above.

The scientific evidence points to increasing risks of serious, irreversible impacts from climate change associated with business-as-usual (BAU) paths for emissions.

The scientific evidence on the causes and future paths of climate change is strengthening all the time. In particular, scientists are now able to attach probabilities to the temperature outcomes and impacts on the natural environment associated with different levels of stabilisation of greenhouse gases in the atmosphere. Scientists also now understand much more about the potential for dynamic feedbacks that have, in previous times of climate change, strongly amplified the underlying physical processes.

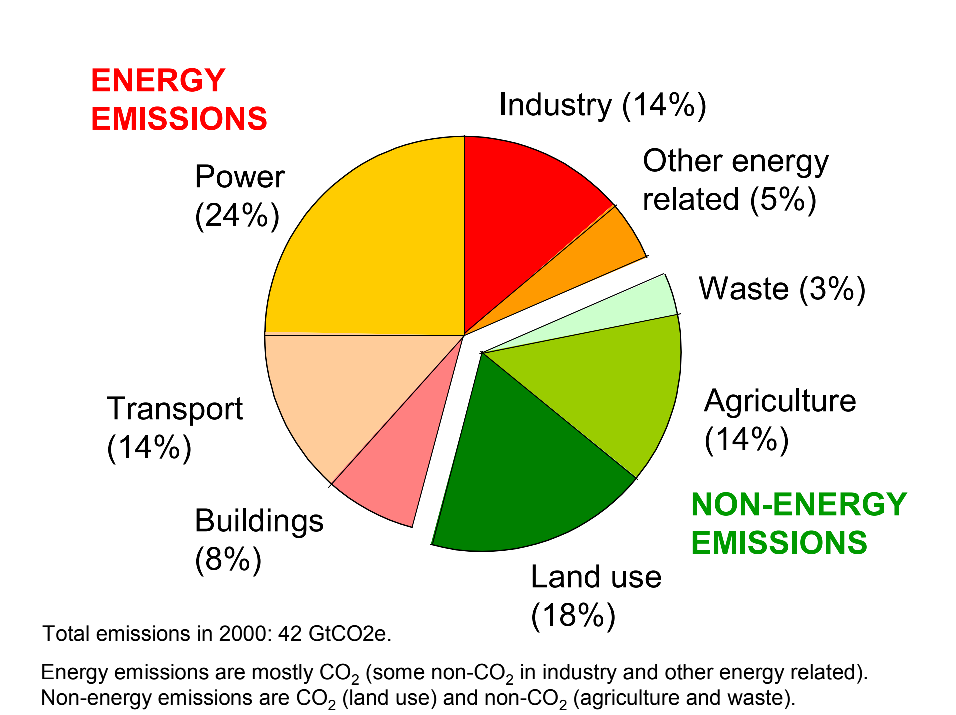
The stocks of greenhouse gases in the atmosphere (including carbon dioxide, methane, nitrous oxides and a number of gases that arise from industrial processes) are rising, as a result of human activity. The sources are summarised in Figure 1 below.

The current level or stock of greenhouse gases in the atmosphere is equivalent to around 430 parts per million (ppm) CO_2 [1], compared with only 280ppm before the Industrial Revolution. These concentrations have already caused the world to warm by more than half a degree Celsius and will lead to at least a further half degree warming over the next few decades, because of the inertia in the climate system.

Even if the annual flow of emissions did not increase beyond today's rate, the stock of greenhouse gases in the atmosphere would reach double pre-industrial levels by 2050 - that is 550ppm CO_2e - and would continue growing thereafter. But the annual flow of emissions is accelerating, as fast-growing economies invest in high-carbon infrastructure and as demand for energy and transport increases around the world. The level of 550ppm CO_2e could be reached as early as 2035. At this level there is at least a 77% chance - and perhaps up to a 99% chance, depending on the climate model used - of a global average temperature rise exceeding 2°C.

[1] Referred to hereafter as CO_2 equivalent, CO_2e

Figure 1 Greenhouse-gas emissions in 2000, by source



Source: Prepared by Stern Review, from data drawn from World Resources Institute Climate Analysis Indicators Tool (CAIT) on-line database version 3.0.

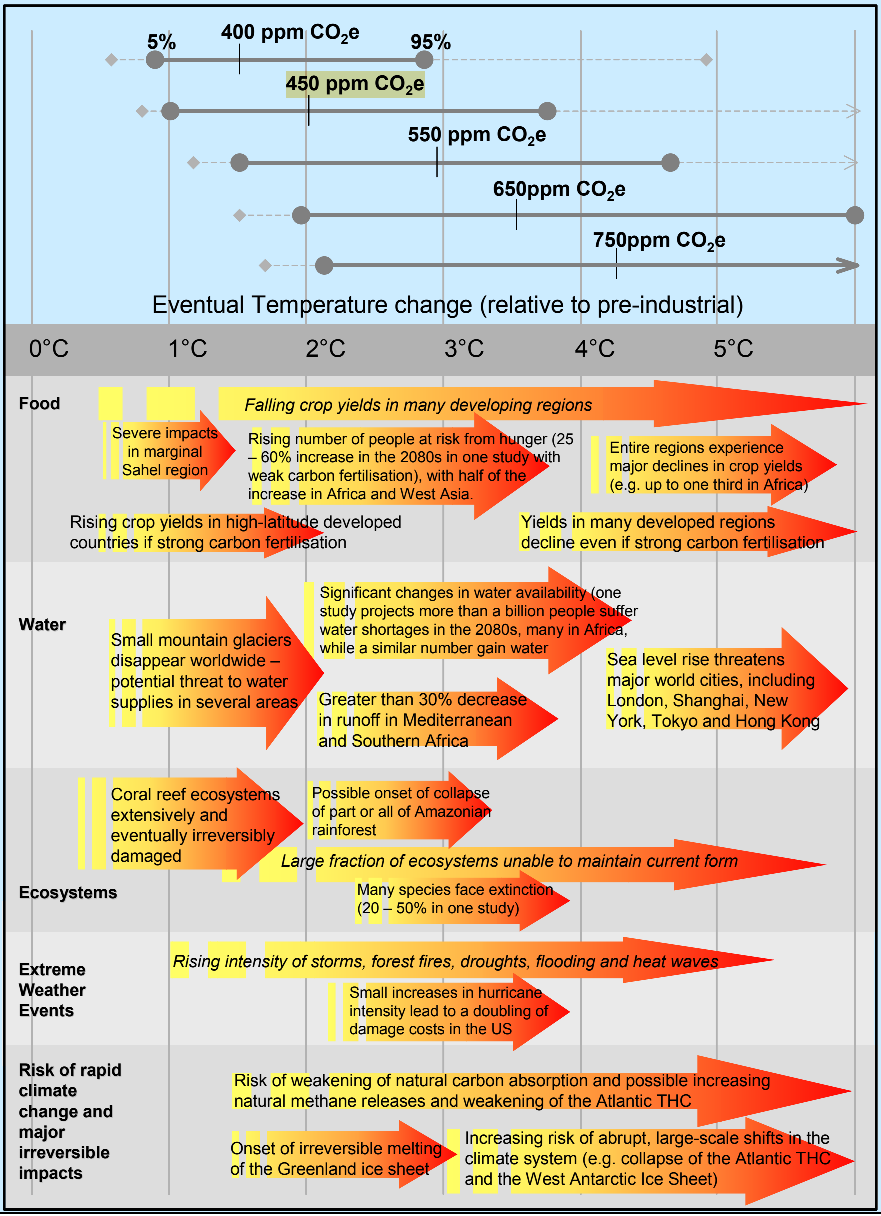
Under a BAU scenario, the stock of greenhouse gases could more than treble by the end of the century, giving at least a 50% risk of exceeding 5°C global average temperature change during the following decades. This would take humans into unknown territory. An illustration of the scale of such an increase is that we are now only around 5°C warmer than in the last ice age.

Such changes would transform the physical geography of the world. A radical change in the physical geography of the world must have powerful implications for the human geography - where people live, and how they live their lives.

Figure 2 summarises the scientific evidence of the links between concentrations of greenhouse gases in the atmosphere, the probability of different levels of global average temperature change, and the physical impacts expected for each level. The risks of serious, irreversible impacts of climate change increase strongly as concentrations of greenhouse gases in the atmosphere rise.

Figure 2 Stabilisation levels and probability ranges for temperature increases

The figure below illustrates the types of impacts that could be experienced as the world comes into equilibrium with more greenhouse gases. The top panel shows the range of temperatures projected at stabilisation levels between 400ppm and 750ppm CO_2e at equilibrium. The solid horizontal lines indicate the 5 - 95% range based on climate sensitivity estimates from the IPCC 2001[2] and a recent Hadley Centre ensemble study[3]. The vertical line indicates the mean of the 50th percentile point. The dashed lines show the 5 - 95% range based on eleven recent studies[4]. The bottom panel illustrates the range of impacts expected at different levels of warming. The relationship between global average temperature changes and regional climate changes is very uncertain, especially with regard to changes in precipitation (see Box 4.2). This figure shows potential changes based on current scientific literature.



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[2] Wigley, T.M.L. and S.C.B. Raper (2001): 'Interpretation of high projections for global-mean warming', Science **293**: 451-454 based on Intergovernmental Panel on Climate Change (2001): 'Climate change 2001: the scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change' [Houghton JT, Ding Y, Griggs DJ, et al. (eds.)], Cambridge: Cambridge University Press.

[3] Murphy, J.M., D.M.H. Sexton D.N. Barnett et al. (2004): 'Quantification of modelling uncertainties in a large ensemble of climate change simulations', Nature **430**: 768 - 772

[4] Meinshausen, M. (2006): 'What does a 2°C target mean for greenhouse gas concentrations? A brief analysis based on multi-gas emission pathways and several climate sensitivity uncertainty estimates', Avoiding dangerous climate change, in H.J. Schellnhuber et al. (eds.), Cambridge: Cambridge University Press, pp.265 - 280.

Climate change threatens the basic elements of life for people around the world - access to water, food production, health, and use of land and the environment.

Estimating the economic costs of climate change is challenging, but there is a range of methods or approaches that enable us to assess the likely magnitude of the risks and compare them with the costs. This Review considers three of these approaches.

This Review has first considered in detail the physical impacts on economic activity, on human life and on the environment.

On current trends, average global temperatures will rise by 2 - 3°C within the next fifty years or so. [5] The Earth will be committed to several degrees more warming if emissions continue to grow.

Warming will have many severe impacts, often mediated through water:

- Melting glaciers will initially increase flood risk and then strongly reduce water supplies, eventually threatening one-sixth of the world's population, predominantly in the Indian sub-continent, parts of China, and the Andes in South America.

- Declining crop yields, especially in Africa, could leave hundreds of millions without the ability to produce or purchase sufficient food. At mid to high latitudes, crop yields may increase for moderate temperature rises (2 - 3°C), but then decline with greater amounts of warming. At 4°C and above, global food production is likely to be seriously affected.

- In higher latitudes, cold-related deaths will decrease. But climate change will increase worldwide deaths from malnutrition and heat stress. Vector-borne diseases such as malaria and dengue fever could become more widespread if effective control measures are not in place.

- Rising sea levels will result in tens to hundreds of millions more people flooded each year with warming of 3 or 4°C. There will be serious risks and increasing pressures for coastal protection in South East Asia (Bangladesh and Vietnam), small islands in the Caribbean and the Pacific, and large coastal cities, such as Tokyo, New York, Cairo and London. According to one estimate, by the middle of the century, 200 million people may become permanently displaced due to rising sea levels, heavier floods, and more intense droughts.

- Ecosystems will be particularly vulnerable to climate change, with around 15 - 40% of species potentially facing extinction after only 2°C of warming. And ocean acidification, a direct result of rising carbon dioxide levels, will have major effects on marine ecosystems, with possible adverse consequences on fish stocks.

[5] All changes in global mean temperature are expressed relative to pre-industrial levels (1750 - 1850).

The damages from climate change will accelerate as the world gets warmer.

Higher temperatures will increase the chance of triggering abrupt and large-scale changes.

- Warming may induce sudden shifts in regional weather patterns such as the monsoon rains in South Asia or the El Niño phenomenon - changes that would have severe consequences for water availability and flooding in tropical regions and threaten the livelihoods of millions of people.

- A number of studies suggest that the Amazon rainforest could be vulnerable to climate change, with models projecting significant drying in this region. One model, for example, finds that the Amazon rainforest could be significantly, and possibly irrevocably, damaged by a warming of 2 - 3°C.

- The melting or collapse of ice sheets would eventually threaten land which today is home to 1 in every 20 people.

While there is much to learn about these risks, the temperatures that may result from unabated climate change will take the world outside the range of human experience. This points to the possibility of very damaging consequences.

The impacts of climate change are not evenly distributed - the poorest countries and people will suffer earliest and most. And if and when the damages appear it will be too late to reverse the process. Thus we are forced to look a long way ahead.

Climate change is a grave threat to the developing world and a major obstacle to continued poverty reduction across its many dimensions. First, developing regions are at a geographic disadvantage: they are already warmer, on average, than developed regions, and they also suffer from high rainfall variability. As a result, further warming will bring poor countries high costs and few benefits. Second, developing countries - in particular the poorest - are heavily dependent on agriculture, the most climate-sensitive of all economic sectors, and suffer from inadequate health provision and low-quality public services. Third, their low incomes and vulnerabilities make adaptation to climate change particularly difficult.

Because of these vulnerabilities, climate change is likely to reduce further already low incomes and increase illness and death rates in developing countries. Falling farm incomes will increase poverty and reduce the ability of households to invest in a better future, forcing them to use up meagre savings just to survive. At a national level, climate change will cut revenues and raise spending needs, worsening public finances.

Many developing countries are already struggling to cope with their current climate. Climatic shocks cause setbacks to economic and social development in developing countries today even with temperature increases of less than 1°C.. The impacts of unabated climate change, - that is, increases of 3 or 4°C and upwards - will be to increase the risks and costs of these events very powerfully.

Impacts on this scale could spill over national borders, exacerbating the damage further. Rising sea levels and other climate-driven changes could drive millions of people to migrate: more than a fifth of Bangladesh could be under water with a 1m rise in sea levels, which is a possibility by the end of the century. Climate-related shocks have sparked violent conflict in the past, and conflict is a serious risk in areas such as West Africa, the Nile Basin and Central Asia.

Climate change may initially have small positive effects for a few developed countries, but is likely to be very damaging for the much higher temperature increases expected by mid- to late-century under BAU scenarios.

In higher latitude regions, such as Canada, Russia and Scandinavia, climate change may lead to net benefits for temperature increases of 2 or 3°C, through higher agricultural yields, lower winter mortality, lower heating requirements, and a possible boost to tourism. But these regions will also experience the most rapid rates of warming, damaging infrastructure, human health, local livelihoods and biodiversity.

Developed countries in lower latitudes will be more vulnerable - for example, water availability and crop yields in southern Europe are expected to decline by 20% with a 2°C increase in global temperatures. Regions where water is already scarce will face serious difficulties and growing costs.

The increased costs of damage from extreme weather (storms, hurricanes, typhoons, floods, droughts, and heat waves) counteract some early benefits of climate change and will increase rapidly at higher temperatures. Based on simple extrapolations, costs of extreme weather alone could reach 0.5 - 1% of world GDP per annum by the middle of the century, and will keep rising if the world continues to warm.

- A 5 or 10% increase in hurricane wind speed, linked to rising sea temperatures, is predicted approximately to double annual damage costs, in the USA.

- In the UK, annual flood losses alone could increase from 0.1% of GDP today to 0.2 - 0.4% of GDP once the increase in global average temperatures reaches 3 or 4°C.

- Heat waves like that experienced in 2003 in Europe, when 35,000 people died and agricultural losses reached $15 billion, will be commonplace by the middle of the century.

At higher temperatures, developed economies face a growing risk of large-scale shocks - for example, the rising costs of extreme weather events could affect global financial markets through higher and more volatile costs of insurance.

Integrated assessment models provide a tool for estimating the total impact on the economy; our estimates suggest that this is likely to be higher than previously suggested.

The second approach to examining the risks and costs of climate change adopted in the Review is to use integrated assessment models to provide aggregate monetary estimates.

Formal modelling of the overall impact of climate change in monetary terms is a formidable challenge, and the limitations to modelling the world over two centuries or more demand great caution in interpreting results. However, as we have explained, the lags from action to effect are very long and the quantitative analysis needed to inform action will depend on such long-range modelling exercises. The monetary impacts of climate change are now expected to be more serious than many earlier studies suggested, not least because those studies tended to exclude some of the most uncertain but potentially most damaging impacts. Thanks to recent advances in the science, it is now possible to examine these risks more directly, using probabilities.

Most formal modelling in the past has used as a starting point a scenario of 2-3°C warming. In this temperature range, the cost of climate change could be equivalent to a permanent loss of around 0-3% in global world output compared with what could have been achieved in a world without climate change. Developing countries will suffer even higher costs.

However, those earlier models were too optimistic about warming: more recent evidence indicates that temperature changes resulting from BAU trends in emissions may exceed 2-3°C by the end of this century. This increases the likelihood of a wider range of impacts than previously considered. Many of these impacts, such as abrupt and large-scale climate change, are more difficult to quantify. With 5-6°C warming - which is a real possibility for the next century - existing models that include the risk of abrupt and large-scale climate change estimate an average 5-10% loss in global GDP, with poor countries suffering costs in excess of 10% of GDP. Further, there is some evidence of small but significant risks of temperature rises even above this range. Such temperature increases would take us into territory unknown to human experience and involve radical changes in the world around us.

With such possibilities on the horizon, it was clear that the modelling framework used by this Review had to be built around the economics of risk. Averaging across possibilities conceals risks. The risks of outcomes much worse than expected are very real and they could be catastrophic. Policy on climate change is in large measure about reducing these risks. They cannot be fully eliminated, but they can be substantially reduced. Such a modelling framework has to take into account ethical judgements on the distribution of income and on how to treat future generations.

The analysis should not focus only on narrow measures of income like GDP. The consequences of climate change for health and for the environment are likely to be severe. Overall comparison of different strategies will include evaluation of these consequences too. Again, difficult conceptual, ethical and measurement issues are involved, and the results have to be treated with due circumspection.

The Review uses the results from one particular model, PAGE2002, to illustrate how the estimates derived from these integrated assessment models change in response to updated scientific evidence on the probabilities attached to degrees of temperature rise. The choice of model was guided by our desire to analyse risks explicitly - this is one of the very few models that would allow that exercise. Further, its underlying assumptions span the range of previous studies. We have used this model with one set of data consistent with the climate predictions of the 2001 report of the Intergovernmental Panel on Climate Change, and with one set that includes a small increase in the amplifying feedbacks in the climate system. This increase illustrates one area of the increased risks of climate change that have appeared in the peer-reviewed scientific literature published since 2001.

We have also considered how the application of appropriate discount rates, assumptions about the equity weighting attached to the valuation of impacts in poor countries, and estimates of the impacts on mortality and the environment would increase the estimated economic costs of climate change.

Using this model, and including those elements of the analysis that can be incorporated at the moment, we estimate the total cost over the next two centuries of climate change associated under BAU emissions involves impacts and risks that are equivalent to an average reduction in global per-capita consumption of at least 5%, now and forever. While this cost estimate is already strikingly high, it also leaves out much that is important.

The cost of BAU would increase still further, were the model systematically to take account of three important factors:

- First, including direct impacts on the environment and human health (sometimes called 'non-market' impacts) increases our estimate of the total cost of climate change on this path from 5% to 11% of global per-capita consumption. There are difficult analytical and ethical issues of measurement here. The methods used in this model are fairly conservative in the value they assign to these impacts.

- Second, some recent scientific evidence indicates that the climate system may be more responsive to greenhouse-gas emissions than previously thought, for example because of the existence of amplifying feedbacks such as the release of methane and weakening of carbon sinks. Our estimates, based on modelling a limited increase in this responsiveness, indicate that the potential scale of the climate response could increase the cost of climate change on the BAU path from 5% to 7% of global consumption, or from 11% to 14% if the non-market impacts described above are included.

- Third, a disproportionate share of the climate-change burden falls on poor regions of the world. If we weight this unequal burden appropriately, the estimated global cost of climate change at 5-6°C warming could be more than one-quarter higher than without such weights.

Putting these additional factors together would increase the total cost of BAU climate change to the equivalent of around a 20% reduction in consumption per head, now and into the future.

In summary, analyses that take into account the full ranges of both impacts and possible outcomes - that is, that employ the basic economics of risk - suggest that BAU climate change will reduce welfare by an amount equivalent to a reduction in consumption per head of between 5 and 20%. Taking account of the increasing scientific evidence of greater risks, of aversion to the possibilities of catastrophe, and of a broader approach to the consequences than implied by narrow output measures, the appropriate estimate is likely to be in the upper part of this range.

Economic forecasting over just a few years is a difficult and imprecise task. The analysis of climate change requires, by its nature, that we look out over 50, 100, 200 years and more. Any such modelling requires caution and humility, and the results are specific to the model and its assumptions. They should not be endowed with a precision and certainty that is simply impossible to achieve. Further, some of the big uncertainties in the science and the economics concern the areas we know least about (for example, the impacts of very high temperatures), and for good reason - this is unknown territory. The main message from these models is that when we try to take due account of the upside risks and uncertainties, the probability-weighted costs look very large. Much (but not all) of the risk can be reduced through a strong mitigation policy, and we argue that this can be achieved at a far lower cost than those calculated for the impacts. In this sense, mitigation is a highly productive investment.

Emissions have been, and continue to be, driven by economic growth; yet stabilisation of greenhouse-gas concentrations in the atmosphere is feasible and consistent with continued growth.

CO_2 emissions per head have been strongly correlated with GDP per head. As a result, since 1850, North America and Europe have produced around 70% of all the CO_2 emissions due to energy production, while developing countries have accounted for less than one quarter. Most future emissions growth will come from today's developing countries, because of their more rapid population and GDP growth and their increasing share of energy-intensive industries.

Yet despite the historical pattern and the BAU projections, the world does not need to choose between averting climate change and promoting growth and development. Changes in energy technologies and the structure of economies have reduced the responsiveness of emissions to income growth, particularly in some of the richest countries. With strong, deliberate policy choices, it is possible to 'decarbonise' both developed and developing economies on the scale required for climate stabilisation, while maintaining economic growth in both.

Stabilisation - at whatever level - requires that annual emissions be brought down to the level that balances the Earth's natural capacity to remove greenhouse gases from the atmosphere. The longer emissions remain above this level, the higher the final stabilisation level. In the long term, annual global emissions will need to be reduced to below 5 $GtCO_2e$, the level that the earth can absorb without adding to the concentration of GHGs in the atmosphere. This is more than 80% below the absolute level of current annual emissions.

This Review has focused on the feasibility and costs of stabilisation of greenhouse gas concentrations in the atmosphere in the range of 450-550ppm CO_2e.

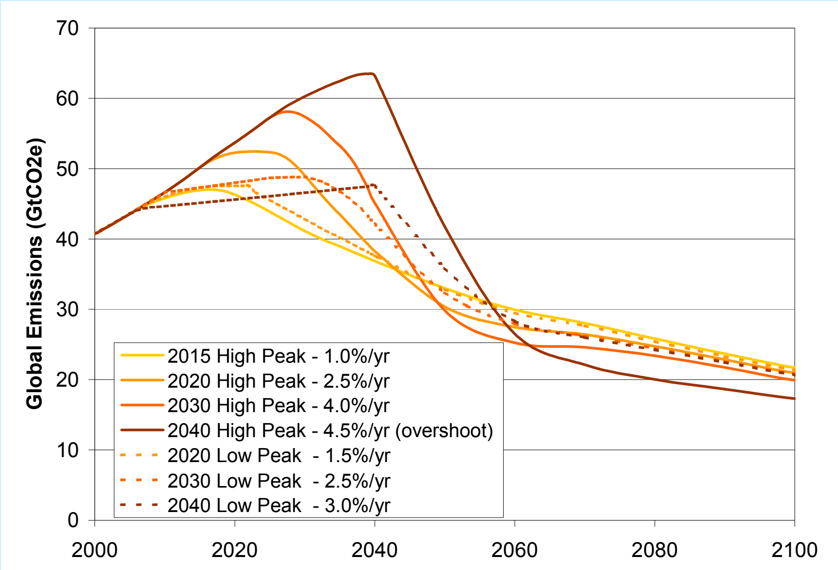
Stabilising at or below 550ppm CO_2e would require global emissions to peak in the next 10 - 20 years, and then fall at a rate of at least 1 - 3% per year. The range of paths is illustrated in Figure 3. By 2050, global emissions would need to be around 25% below current levels. These cuts will have to be made in the context of a world economy in 2050 that may be 3 - 4 times larger than today - so emissions per unit of GDP would need to be just one quarter of current levels by 2050.

To stabilise at 450ppm CO_2e, without overshooting, global emissions would need to peak in the next 10 years and then fall at more than 5% per year, reaching 70% below current levels by 2050.

Theoretically it might be possible to "overshoot" by allowing the atmospheric GHG concentration to peak above the stabilisation level and then fall, but this would be both practically very difficult and very unwise. Overshooting paths involve greater risks, as temperatures will also rise rapidly and peak at a higher level for many decades before falling back down. Also, overshooting requires that emissions subsequently be reduced to extremely low levels, below the level of natural carbon absorption, which may not be feasible. Furthermore, if the high temperatures were to weaken the capacity of the Earth to absorb carbon - as becomes more likely with overshooting - future emissions would need to be cut even more rapidly to hit any given stabilisation target for atmospheric concentration.

Figure 3 Illustrative emissions paths to stabilise at 550ppm CO_2e.

The figure below shows six illustrative paths to stabilisation at 550ppm CO_2e. The rates of emissions cuts given in the legend are the *maximum* 10-year average rate of decline of global emissions. The figure shows that delaying emissions cuts (shifting the peak to the right) means that emissions must be reduced more rapidly to achieve the same stabilisation goal. The rate of emissions cuts is also very sensitive to the height of the peak. For example, if emissions peak at 48 $GtCO_2$ rather than 52 $GtCO_2$ in 2020, the rate of cuts is reduced from 2.5%/yr to 1.5%/yr.



Source: Reproduced by the Stern Review based on Meinshausen, M. (2006): 'What does a 2°C target mean for greenhouse gas concentrations? A brief analysis based on multi-gas emission pathways and several climate sensitivity uncertainty estimates', Avoiding dangerous climate change, in H.J. Schellnhuber et al. (eds.), Cambridge: Cambridge University Press, pp.265 - 280.

Achieving these deep cuts in emissions will have a cost. The Review estimates the annual costs of stabilisation at 500-550ppm CO_2e to be around 1% of GDP by 2050 - a level that is significant but manageable.

Reversing the historical trend in emissions growth, and achieving cuts of 25% or more against today's levels is a major challenge. Costs will be incurred as the world shifts from a high-carbon to a low-carbon trajectory. But there will also be business opportunities as the markets for low-carbon, high-efficiency goods and services expand.

Greenhouse-gas emissions can be cut in four ways. Costs will differ considerably depending on which combination of these methods is used, and in which sector:

- Reducing demand for emissions-intensive goods and services
- Increased efficiency, which can save both money and emissions
- Action on non-energy emissions, such as avoiding deforestation
- Switching to lower-carbon technologies for power, heat and transport

Estimating the costs of these changes can be done in two ways. One is to look at the resource costs of measures, including the introduction of low-carbon technologies and changes in land use, compared with the costs of the BAU alternative. This provides an upper bound on costs, as it does not take account of opportunities to respond involving reductions in demand for high-carbon goods and services.

The second is to use macroeconomic models to explore the system-wide effects of the transition to a low-carbon energy economy. These can be useful in tracking the dynamic interactions of different factors over time, including the response of economies to changes in prices. But they can be complex, with their results affected by a whole range of assumptions.

On the basis of these two methods, central estimate is that stabilisation of greenhouse gases at levels of 500-550ppm CO_2e will cost, on average, around 1% of annual global GDP by 2050. This is significant, but is fully consistent with continued growth and development, in contrast with unabated climate change, which will eventually pose significant threats to growth.

Resource cost estimates suggest that an upper bound for the expected annual cost of emissions reductions consistent with a trajectory leading to stabilisation at 550ppm CO_2e is likely to be around 1% of GDP by 2050.

This Review has considered in detail the potential for, and costs of, technologies and measures to cut emissions across different sectors. As with the impacts of climate change, this is subject to important uncertainties. These include the difficulties of estimating the costs of technologies several decades into the future, as well as the way in which fossil-fuel prices evolve in the future. It is also hard to know how people will respond to price changes.

The precise evolution of the mitigation effort, and the composition across sectors of emissions reductions, will therefore depend on all these factors. But it is possible to make a central projection of costs across a portfolio of likely options, subject to a range.

The technical potential for efficiency improvements to reduce emissions and costs is substantial. Over the past century, efficiency in energy supply improved ten-fold or more in developed countries, and the possibilities for further gains are far from being exhausted. Studies by the International Energy Agency show that, by 2050, energy efficiency has the potential to be the biggest single source of emissions savings in the energy sector. This would have both environmental and economic benefits: energy-efficiency measures cut waste and often save money.

Non-energy emissions make up one-third of total greenhouse-gas emissions; action here will make an important contribution. A substantial body of evidence suggests that action to prevent further deforestation would be relatively cheap compared with other types of mitigation, if the right policies and institutional structures are put in place.

Large-scale uptake of a range of clean power, heat, and transport technologies is required for radical emission cuts in the medium to long term. The power sector around the world will have to be least 60%, and perhaps as much as 75%, decarbonised by 2050 to stabilise at or below 550ppm CO_2e. Deep cuts in the transport sector are likely to be more difficult in the shorter term, but will ultimately be needed. While many of the technologies to achieve this already exist, the priority is to bring down their costs so that they are competitive with fossil-fuel alternatives under a carbon-pricing policy regime.

A portfolio of technologies will be required to stabilise emissions. It is highly unlikely that any single technology will deliver all the necessary emission savings, because all technologies are subject to constraints of some kind, and because of the wide range of activities and sectors that generate greenhouse-gas emissions. It is also uncertain which technologies will turn out to be cheapest. Hence a portfolio will be required for low-cost abatement.

The shift to a low-carbon global economy will take place against the background of an abundant supply of fossil fuels. That is to say, the stocks of hydrocarbons that are profitable to extract (under current policies) are more than enough to take the world to levels of greenhouse-gas concentrations well beyond 750ppm CO_2e, with very dangerous consequences. Indeed, under BAU, energy users are likely to switch towards more carbon-intensive coal and oil shales, increasing rates of emissions growth.

Even with very strong expansion of the use of renewable energy and other low-carbon energy sources, hydrocarbons may still make over half of global energy supply in 2050. Extensive carbon capture and storage would allow this continued use of fossil fuels without damage to the atmosphere, and also guard against the danger of strong climate-change policy being undermined at some stage by falls in fossil-fuel prices.

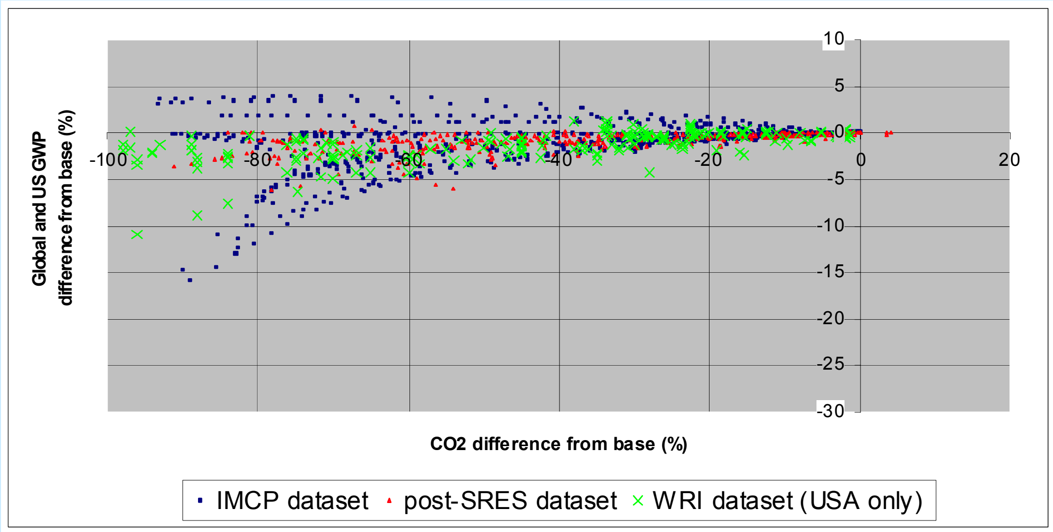
Estimates based on the likely costs of these methods of emissions reduction show that the annual costs of stabilising at around 550ppm CO_2e are likely to be around 1% of global GDP by 2050, with a range from –1% (net gains) to +3.5% of GDP.

Looking at broader macroeconomic models confirms these estimates.

The second approach adopted by the Review was based comparisons of a broad range of macro-economic model estimates (such as that presented in Figure 4 below). This comparison found that the costs for stabilisation at 500-550ppm CO_2e were centred on 1% of GDP by 2050, with a range of -2% to +5% of GDP. The range reflects a number of factors, including the pace of technological innovation and the efficiency with which policy is applied across the globe: the faster the innovation and the greater the efficiency, the lower the cost. These factors can be influenced by policy.

The average expected cost is likely to remain around 1% of GDP from mid-century, but the range of estimates around the 1% diverges strongly thereafter, with some falling and others rising sharply by 2100, reflecting the greater uncertainty about the costs of seeking out ever more innovative methods of mitigation.

Figure 4 Model cost projections scatter plot
Costs of CO_2 reductions as a fraction of world GDP against level of reduction



Source: Barker, T., M.S. Qureshi and J. Köhler (2006): 'The costs of greenhouse-gas mitigation with induced technological change: A Meta-Analysis of estimates in the literature', 4CMR, Cambridge Centre for Climate Change Mitigation Research, Cambridge: University of Cambridge.

A broad range of modelling studies, which include exercises undertaken by the IMCP, EMF and USCCSP as well at work commissioned by the IPCC, show that costs for 2050 consistent with an emissions trajectory leading to stabilisation at around 500-550ppm CO2e are clustered in the range of –2% to 5% of GDP, with an average around 1% of GDP. The range reflects uncertainties over the scale of mitigation required, the pace of technological innovation and the degree of policy flexibility.

The figure above uses Barker's combined three-model dataset to show the reduction in annual CO_2 emissions from the baseline and the associated changes in world GDP. The wide range of model results reflects the design of the models and the choice of assumptions included within them, which itself reflects uncertainties and differing approaches inherent in projecting the future. This shows that the full range of estimates drawn from a variety of stabilisation paths and years extends from –4% of GDP (that is, net gains) to +15% of GDP costs, but this mainly reflects outlying studies; most estimates are still centred around 1% of GDP. In particular, the models arriving at higher cost estimates make assumptions about technological progress that are very pessimistic by historical standards.

Stabilisation at 450ppm CO_2e is already almost out of reach, given that we are likely to reach this level within ten years and that there are real difficulties of making the sharp reductions required with current and foreseeable technologies. Costs rise significantly as mitigation efforts become more ambitious or sudden. Efforts to reduce emissions rapidly are likely to be very costly.

An important corollary is that there is a high price to delay. Delay in taking action on climate change would make it necessary to accept both more climate change and, eventually, higher mitigation costs. Weak action in the next 10-20 years would put stabilisation even at 550ppm CO_2e beyond reach – and this level is already associated with significant risks.

The transition to a low-carbon economy will bring challenges for competitiveness but also opportunities for growth.

Costs of mitigation of around 1% of GDP are small relative to the costs and risks of climate change that will be avoided. However, for some countries and some sectors, the costs will be higher. There may be some impacts on the competitiveness of a small number of internationally traded products and processes. These should not be overestimated, and can be reduced or eliminated if countries or sectors act together; nevertheless, there will be a transition to be managed. For the economy as a whole, there will be benefits from innovation that will offset some of these costs. All economies undergo continuous structural change; the most successful economies are those that have the flexibility and dynamism to embrace the change.

There are also significant new opportunities across a wide range of industries and services. Markets for low-carbon energy products are likely to be worth at least $500bn per year by 2050, and perhaps much more. Individual companies and countries should position themselves to take advantage of these opportunities.

Climate-change policy can help to root out existing inefficiencies. At the company level, implementing climate policies may draw attention to money-saving opportunities. At the economy-wide level, climate-change policy may be a lever for reforming inefficient energy systems and removing distorting energy subsidies, on which governments around the world currently spend around $250bn a year.

Policies on climate change can also help to achieve other objectives**.** These co-benefits can significantly reduce the overall cost to the economy of reducing greenhouse-gas emissions. If climate policy is designed well, it can, for example, contribute to reducing ill-health and mortality from air pollution, and to preserving forests that contain a significant proportion of the world's biodiversity.

National objectives for energy security can also be pursued alongside climate change objectives. Energy efficiency and diversification of energy sources and supplies support energy security, as do clear long-term policy frameworks for investors in power generation. Carbon capture and storage is essential to maintain the role of coal in providing secure and reliable energy for many economies.

Reducing the expected adverse impacts of climate change is therefore both highly desirable and feasible.

This conclusion follows from a comparison of the above estimates of the costs of mitigation with the high costs of inaction described from our first two methods (the aggregated and the disaggregated) of assessing the risks and costs of climate change impacts.

The third approach to analysing the costs and benefits of action on climate change adopted by this Review compares the marginal costs of abatement with the social cost of carbon. This approach compares estimates of the changes in the expected benefits and costs over time from a little extra reduction in emissions, and avoids large-scale formal economic models.

Preliminary calculations adopting the approach to valuation taken in this Review suggest that the social cost of carbon today, if we remain on a BAU trajectory, is of the order of $85 per tonne of CO_2 - higher than typical numbers in the literature, largely because we treat risk explicitly and incorporate recent evidence on the risks, but nevertheless well within the range of published estimates. This number is well above marginal abatement costs in many sectors. Comparing the social costs of carbon on a BAU trajectory and on a path towards stabilisation at 550ppm CO2e, we estimate the excess of benefits over costs, in net present value terms, from implementing strong mitigation policies this year, shifting the world onto the better path: the net benefits would be of the order of $2.5 trillion. This figure will increase over time. This is not an estimate of net benefits occurring in this year, but a measure of the benefits that could flow from actions taken this year; many of the costs and benefits would be in the medium to long term.

Even if we have sensible policies in place, the social cost of carbon will also rise steadily over time, making more and more technological options for mitigation cost-effective. This does not mean that consumers will always face rising prices for the goods and services that they currently enjoy, as innovation driven by strong policy will ultimately reduce the carbon intensity of our economies, and consumers will then see reductions in the prices that they pay as low-carbon technologies mature.

The three approaches to the analysis of the costs of climate change used in the Review all point to the desirability of strong action, given estimates of the costs of action on mitigation. But how much action? The Review goes on to examine the economics of this question.

The current evidence suggests aiming for stabilisation somewhere within the range 450 - 550ppm CO_2e. Anything higher would substantially increase the risks of very harmful impacts while reducing the expected costs of mitigation by comparatively little. Aiming for the lower end of this range would mean that the costs of mitigation would be likely to rise rapidly. Anything lower would certainly impose very high adjustment costs in the near term for small gains and might not even be feasible, not least because of past delays in taking strong action.

Uncertainty is an argument for a more, not less, demanding goal, because of the size of the adverse climate-change impacts in the worst-case scenarios.

The ultimate concentration of greenhouse gases determines the trajectory for estimates of the social cost of carbon; these also reflect the particular ethical judgements and approach to the treatment of uncertainty embodied in the modelling. Preliminary work for this Review suggests that, if the target were between 450-550ppm CO_2e, then the social cost of carbon would start in the region of $25-30 per tonne of CO_2 – around one third of the level if the world stays with BAU.

The social cost of carbon is likely to increase steadily over time because marginal damages increase with the stock of GHGs in the atmosphere, and that stock rises over time. Policy should therefore ensure that abatement efforts at the margin also intensify over time. But it should also foster the development of technology that can drive down the average costs of abatement; although pricing carbon, by itself, will not be sufficient to bring forth all the necessary innovation, particularly in the early years.

The first half of the Review therefore demonstrates that strong action on climate change, including both mitigation and adaptation, is worthwhile, and suggests appropriate goals for climate-change policy.

The second half of the Review examines the appropriate form of such policy, and how it can be placed within a framework of international collective action.

Policy to reduce emissions should be based on three essential elements: carbon pricing, technology policy, and removal of barriers to behavioural change.

There are complex challenges in reducing greenhouse-gas emissions. Policy frameworks must deal with long time horizons and with interactions with a range of other market imperfections and dynamics.

A shared understanding of the long-term goals for stabilisation is a crucial guide to policy-making on climate change: it narrows down strongly the range of acceptable emissions paths. But from year to year, flexibility in what, where and when reductions are made will reduce the costs of meeting these stabilisation goals.

Policies should adapt to changing circumstances as the costs and benefits of responding to climate change become clearer over time. They should also build on diverse national conditions and approaches to policy-making. But the strong links between current actions and the long-term goal should be at the forefront of policy.

Three elements of policy for mitigation are essential: a carbon price, technology policy, and the removal of barriers to behavioural change. Leaving out any one of these elements will significantly increase the costs of action.

Establishing a carbon price, through tax, trading or regulation, is an essential foundation for climate-change policy.

The first element of policy is carbon pricing. Greenhouse gases are, in economic terms, an externality: those who produce greenhouse-gas emissions are bringing about climate change, thereby imposing costs on the world and on future generations, but they do not face the full consequences of their actions themselves.

Putting an appropriate price on carbon – explicitly through tax or trading, or implicitly through regulation – means that people are faced with the full social cost of their actions. This will lead individuals and businesses to switch away from high-carbon goods and services, and to invest in low-carbon alternatives. Economic efficiency points to the advantages of a common global carbon price: emissions reductions will then take place wherever they are cheapest.

The choice of policy tool will depend on countries' national circumstances, on the characteristics of particular sectors, and on the interaction between climate-change policy and other policies. Policies also have important differences in their consequences for the distribution of costs across individuals, and their impact on the public finances. Taxation has the advantage of delivering a steady flow of revenue, while, in the case of trading, increasing the use of auctioning is likely to have strong benefits for efficiency, for distribution and for the public finances. Some administrations may choose to focus on trading initiatives, others on taxation or regulation, and others on a mix of policies. And their choices may vary across sectors.

Trading schemes can be an effective way to equalise carbon prices across countries and sectors, and the EU Emissions Trading Scheme is now the centrepiece of European efforts to cut emissions. To reap the benefits of emissions trading, schemes must provide incentives for a flexible and efficient response. Broadening the scope of trading schemes will tend to lower costs and reduce volatility. Clarity and predictability about the future rules and shape of schemes will help to build confidence in a future carbon price.

In order to influence behaviour and investment decisions, investors and consumers must believe that the carbon price will be maintained into the future. This is particularly important for investments in long-lived capital stock. Investments such as power stations, buildings, industrial plants and aircraft last for many decades. If there is a lack of confidence that climate change policies will persist, then businesses may not factor a carbon price into their decision-making. The result may be overinvestment in long-lived, high-carbon infrastructure – which will make emissions cuts later on much more expensive and difficult.

But establishing credibility takes time. The next 10 to 20 years will be a period of transition, from a world where carbon-pricing schemes are in their infancy, to one where carbon pricing is universal and is automatically factored into decision making. In this transitional period, while the credibility of policy is still being established and the international framework is taking shape, it is critical that governments consider how to avoid the risks of locking into a high-carbon infrastructure, including considering whether any additional measures may be justified to reduce the risks.

Policies are required to support the development of a range of low-carbon and high-efficiency technologies on an urgent timescale.

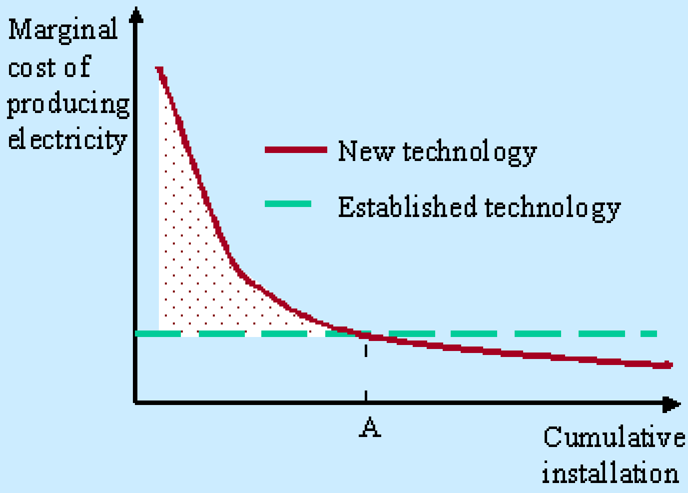
The second element of climate-change policy is technology policy, covering the full spectrum from research and development, to demonstration and early stage deployment. The development and deployment of a wide range of low-carbon technologies is essential in achieving the deep cuts in emissions that are needed. The private sector plays the major role in R&D and technology diffusion, but closer collaboration between government and industry will further stimulate the development of a broad portfolio of low carbon technologies and reduce costs.

Many low-carbon technologies are currently more expensive than the fossil-fuel alternatives. But experience shows that the costs of technologies fall with scale and experience, as shown in Figure 5 below.

Carbon pricing gives an incentive to invest in new technologies to reduce carbon; indeed, without it, there is little reason to make such investments. But investing in new lower-carbon technologies carries risks. Companies may worry that they will not have a market for their new product if carbon-pricing policy is not maintained into the future. And the knowledge gained from research and development is a public good; companies may under-invest in projects with a big social payoff if they fear they will be unable to capture the full benefits. Thus there are good economic reasons to promote new technology directly.

Public spending on research, development and demonstration has fallen significantly in the last two decades and is now low relative to other industries. There are likely to be high returns to a doubling of investments in this area to around $20 billion per annum globally, to support the development of a diverse portfolio of technologies.

Figure 5: The costs of technologies are likely to fall over time



Historical experience of both fossil-fuel and low-carbon technologies shows that as scale increases, costs tend to fall. Economists have fitted 'learning curves' to costs data to estimate the size of this effect. An illustrative curve is shown above for a new electricity-generation technology; the technology is initially much more expensive than the established alternative, but as its scale increases, the costs fall, and beyond Point A it becomes cheaper. Work by the International Energy Agency and others shows that such relationships hold for a range of different energy technologies.

A number of factors explain this, including the effects of learning and economies of scale. But the relationship is more complex than the figure suggests. Step-change improvements in a technology might accelerate progress, while constraints such as the availability of land or materials could result in increasing marginal costs.

In some sectors - particularly electricity generation, where new technologies can struggle to gain a foothold - policies to support the market for early-stage technologies will be critical. The Review argues that the scale of existing deployment incentives worldwide should increase by two to five times, from the current level of around $34 billion per annum. Such measures will be a powerful motivation for innovation across the private sector to bring forward the range of technologies needed.

The removal of barriers to behavioural change is a third essential element, one that is particularly important in encouraging the take-up of opportunities for energy efficiency.

The third element is the removal of barriers to behavioural change. Even where measures to reduce emissions are cost-effective, there may be barriers preventing action. These include a lack of reliable information, transaction costs, and behavioural and organisational inertia. The impact of these barriers can be most clearly seen in the frequent failure to realise the potential for cost-effective energy efficiency measures.

Regulatory measures can play a powerful role in cutting through these complexities, and providing clarity and certainty. Minimum standards for buildings and appliances have proved a cost-effective way to improve performance, where price signals alone may be too muted to have a significant impact.

Information policies, including labelling and the sharing of best practice, can help consumers and businesses make sound decisions, and stimulate competitive markets for low-carbon and high-efficiency goods and services. Financing measures can also help, through overcoming possible constraints to paying the upfront cost of efficiency improvements.

Fostering a shared understanding of the nature of climate change, and its consequences, is critical in shaping behaviour, as well as in underpinning national and international action. Governments can be a catalyst for dialogue through evidence, education, persuasion and discussion. Educating those currently at school about climate change will help to shape and sustain future policy-making, and a broad public and international debate will support today's policy-makers in taking strong action now.

Adaptation policy is crucial for dealing with the unavoidable impacts of climate change, but it has been under-emphasised in many countries.

Adaptation is the only response available for the impacts that will occur over the next several decades before mitigation measures can have an effect.

Unlike mitigation, adaptation will in most cases provide local benefits, realised without long lead times. Therefore some adaptation will occur autonomously, as individuals respond to market or environmental changes. Some aspects of adaptation, such as major infrastructure decisions, will require greater foresight and planning. There are also some aspects of adaptation that require public goods delivering global benefits, including improved information about the climate system and more climate-resilient crops and technologies.

Quantitative information on the costs and benefits of economy-wide adaptation is currently limited. Studies in climate-sensitive sectors point to many adaptation options that will provide benefits in excess of cost. But at higher temperatures, the costs of adaptation will rise sharply and the residual damages remain large. The additional costs of making new infrastructure and buildings resilient to climate change in OECD countries could be $15 – 150 billion each year (0.05 – 0.5% of GDP).

The challenge of adaptation will be particularly acute in developing countries, where greater vulnerability and poverty will limit the capacity to act. As in developed countries, the costs are hard to estimate, but are likely to run into tens of billions of dollars.

Markets that respond to climate information will stimulate adaptation among individuals and firms. Risk-based insurance schemes, for example, provide strong signals about the size of climate risks and therefore encourage good risk management.

Governments have a role in providing a policy framework to guide effective adaptation by individuals and firms in the medium and longer term. There are four key areas:

- High-quality climate information and tools for risk management will help to drive efficient markets. Improved regional climate predictions will be critical, particularly for rainfall and storm patterns.

- Land-use planning and performance standards should encourage both private and public investment in buildings and other long-lived infrastructure to take account of climate change.

- Governments can contribute through long-term polices for climate-sensitive public goods, including natural resources protection, coastal protection, and emergency preparedness.

- A financial safety net may be required for the poorest in society, who are likely to be the most vulnerable to the impacts and least able to afford protection (including insurance).

Sustainable development itself brings the diversification, flexibility and human capital which are crucial components of adaptation. Indeed, much adaptation will simply be an extension of good development practice – for example, promoting overall development, better disaster management and emergency response. Adaptation action should be integrated into development policy and planning at every level.

An effective response to climate change will depend on creating the conditions for international collective action.

This Review has identified many actions that communities and countries can take on their own to tackle climate change.

Indeed, many countries, states and companies are already beginning to act. However, the emissions of most individual countries are small relative to the global total, and very large reductions are required to stabilise greenhouse gas concentrations in the atmosphere. Climate change mitigation raises the classic problem of the provision of a global public good. It shares key characteristics with other environmental challenges that require the international management of common resources to avoid free riding.

The UN Framework Convention on Climate Change (UNFCCC), Kyoto Protocol and a range of other informal partnerships and dialogues provide a framework that supports co-operation, and a foundation from which to build further collective action.

A shared global perspective on the urgency of the problem and on the long-term goals for climate change policy, and an international approach based on multilateral frameworks and co-ordinated action, are essential to respond to the scale of the challenge. International frameworks for action on climate change should encourage and respond to the leadership shown by different countries in different ways, and should facilitate and motivate the involvement of all states. They should build on the principles of effectiveness, efficiency and equity that have already provided the foundations of the existing multilateral framework.

The need for action is urgent: demand for energy and transportation is growing rapidly in many developing countries, and many developed countries are also due to renew a significant proportion of capital stock. The investments made in the next 10-20 years could lock in very high emissions for the next half-century, or present an opportunity to move the world onto a more sustainable path.

International co-operation must cover all aspects of policy to reduce emissions – pricing, technology and the removal of behavioural barriers, as well as action on emissions from land use. And it must promote and support adaptation. There are significant opportunities for action now, including in areas with immediate economic benefits (such as energy efficiency and reduced gas flaring) and in areas where large-scale pilot programmes would generate important experience to guide future negotiations.

Agreement on a broad set of mutual responsibilities across each of the relevant dimensions of action would contribute to the overall goal of reducing the risks of climate change. These responsibilities should take account of costs and the ability to bear them, as well as starting points, prospects for growth and past histories.

Securing broad-based and sustained co-operation requires an equitable distribution of effort across both developed and developing countries. There is no single formula that captures all dimensions of equity, but calculations based on income, historic responsibility and per capita emissions all point to rich countries taking responsibility for emissions reductions of 60-80% from 1990 levels by 2050.

Co-operation can be encouraged and sustained by greater transparency and comparability of national action.

Creating a broadly similar carbon price signal around the world, and using carbon finance to accelerate action in developing countries, are urgent priorities for international co-operation.

A broadly similar price of carbon is necessary to keep down the overall costs of making these reductions, and can be created through tax, trading or regulation. The transfer of technologies to developing countries by the private sector can be accelerated through national action and international co-operation.

The Kyoto Protocol has established valuable institutions to underpin international emissions trading. There are strong reasons to build on and learn from this approach. There are opportunities to use the UNFCCC dialogue and the review of the effectiveness of the Kyoto Protocol, as well as a wide range of informal dialogues, to explore ways to move forward.

Private sector trading schemes are now at the heart of international flows of carbon finance. Linking and expanding regional and sectoral emissions trading schemes, including sub-national and voluntary schemes, requires greater international co-operation and the development of appropriate new institutional arrangements.

Decisions made now on the third phase of the EU ETS provide an opportunity for the scheme to influence, and become the nucleus of, future global carbon markets.

The EU ETS is the world's largest carbon market. The structure of the third phase of the scheme, beyond 2012, is currently under debate. This is an opportunity to set out a clear, long-term vision to place the scheme at the heart of future global carbon markets.

There are a number of elements which will contribute to a credible vision for the EU ETS. The overall EU limit on emissions should be set at a level that ensures scarcity in the market for emissions allowances, with stringent criteria for allocation volumes across all relevant sectors. Clear and frequent information on emissions during the trading period would improve transparency in the market, reducing the risks of unnecessary price spikes or of unexpected collapses.

Clear revision rules covering the basis for allocations in future trading periods would create greater predictability for investors. The possibility of banking (and perhaps borrowing) emissions allowances between periods could help smooth prices over time.

Broadening participation to other major industrial sectors, and to sectors such as aviation, would help deepen the market, and increased use of auctioning would promote efficiency.

Enabling the EU ETS to link with other emerging trading schemes (including in the USA and Japan), and maintaining and developing mechanisms to allow the use of carbon reductions made in developing countries, could improve liquidity while also establishing the nucleus of a global carbon market.

Scaling up flows of carbon finance to developing countries to support effective policies and programmes for reducing emissions would accelerate the transition to a low-carbon economy.

Developing countries are already taking significant action to decouple their economic growth from the growth in greenhouse gas emissions. For example, China has adopted very ambitious domestic goals to reduce energy used for each unit of GDP by 20% from 2006-2010 and to promote the use of renewable energy. India has created an Integrated Energy Policy for the same period that includes measures to expand access to cleaner energy for poor people and to increase energy efficiency.

The Clean Development Mechanism, created by the Kyoto Protocol, is currently the main formal channel for supporting low-carbon investment in developing countries. It allows both governments and the private sector to invest in projects that reduce emissions in fast-growing emerging economies, and provides one way to support links between different regional emissions trading schemes.

In future, a transformation in the scale of, and institutions for, international carbon finance flows will be required to support cost-effective emissions reductions. The incremental costs of low-carbon investments in developing countries are likely to be at least $20-30 billion per year. Providing assistance with these costs will require a major increase in the level of ambition of trading schemes such as the EU ETS. This will also require mechanisms that link private-sector carbon finance to policies and programmes rather than to individual projects. And it should work within a context of national, regional or sectoral objectives for emissions reductions. These flows will be crucial in accelerating private investment and national government action in developing countries.

There are opportunities now to build trust and to pilot new approaches to creating large-scale flows for investment in low-carbon development paths. Early signals from existing emissions trading schemes, including the EU ETS, about the extent to which they will accept carbon credits from developing countries, would help to maintain continuity during this important stage of building markets and demonstrating what is possible.

The International Financial Institutions have an important role to play in accelerating this process: the establishment of a Clean Energy Investment Framework by the World Bank and other multilateral development banks offers significant potential for catalysing and scaling up investment flows.

Greater international co-operation to accelerate technological innovation and diffusion will reduce the costs of mitigation.

The private sector is the major driver of innovation and the diffusion of technologies around the world. But governments can help to promote international collaboration to overcome barriers in this area, including through formal arrangements and through arrangements that promote public-private co-operation such as the Asia Pacific Partnership. Technology co-operation enables the sharing of risks, rewards and progress of technology development and enables co-ordination of priorities.

A global portfolio that emerges from individual national R&D priorities and deployment support may not be sufficiently diverse, and is likely to place too little weight on some technologies that are particularly important for developing countries, such as biomass.

International R&D co-operation can take many forms. Coherent, urgent and broadly based action requires international understanding and co-operation. These may be embodied in formal multilateral agreements that allow countries to pool the risks and rewards for major investments in R&D, including demonstration projects and dedicated international programmes to accelerate key technologies. But formal agreements are only one part of the story - informal arrangements for greater co-ordination and enhanced linkages between national programmes can also play a very prominent role.

Both informal and formal co-ordination of national policies for deployment support can accelerate cost reductions by increasing the scale of new markets across borders. Many countries and US states now have specific national objectives and policy frameworks to support the deployment of renewable energy technologies. Transparency and information-sharing have already helped to boost interest in these markets. Exploring the scope for making deployment instruments tradable across borders could increase the effectiveness of support, including mobilising the resources that will be required to accelerate the widespread deployment of carbon capture and storage and the use of technologies that are particularly appropriate for developing countries.

International co-ordination of regulations and product standards can be a powerful way to encourage greater energy efficiency. It can raise their cost effectiveness, strengthen the incentives to innovate, improve transparency, and promote international trade.

The reduction of tariff and non-tariff barriers for low-carbon goods and services, including within the Doha Development Round of international trade negotiations, could provide further opportunities to accelerate the diffusion of key technologies.

Curbing deforestation is a highly cost-effective way of reducing greenhouse gas emissions.

Emissions from deforestation are very significant – they are estimated to represent more than 18% of global emissions, a share greater than is produced by the global transport sector.

Action to preserve the remaining areas of natural forest is needed urgently. Large-scale pilot schemes are required to explore effective approaches to combining national action and international support.

Policies on deforestation should be shaped and led by the nation where the particular forest stands. But those countries should receive strong help from the international community, which benefits from their actions to reduce deforestation. At a national level, defining property rights to forestland, and determining the rights and responsibilities of landowners, communities and loggers, is key to effective forest management. This should involve local communities, respect informal rights and social structures, work with development goals and reinforce the process of protecting the forests.

Research carried out for this report indicates that the opportunity cost of forest protection in 8 countries responsible for 70 per cent of emissions from land use could be around $5 billion per annum initially, although over time marginal costs would rise.

Compensation from the international community should take account of the opportunity costs of alternative uses of the land, the costs of administering and enforcing protection, and the challenges of managing the political transition as established interests are displaced.

Carbon markets could play an important role in providing such incentives in the longer term. But there are short-term risks of destabilising the crucial process of strengthening existing strong carbon markets if deforestation is integrated without agreements that strongly increase demand for emissions reductions. These agreements must be based on an understanding of the scale of transfers likely to be involved.

Adaptation efforts in developing countries must be accelerated and supported, including through international development assistance.

The poorest developing countries will be hit earliest and hardest by climate change, even though they have contributed little to causing the problem. Their low incomes make it difficult to finance adaptation. The international community has an obligation to support them in adapting to climate change. Without such support there is a serious risk that development progress will be undermined.

It is for the developing countries themselves to determine their approach to adaptation in the context of their own circumstances and aspirations. Rapid growth and development will enhance countries' ability to adapt. The additional costs to developing countries of adapting to climate change could run into tens of billions of dollars.

The scale of the challenge makes it more urgent than ever for developed countries to honour their existing commitments – made in Monterrey in 2002, and strengthened at EU Councils in June 2005 and at the July 2005 G8 Gleneagles Summit – to double aid flows by 2010.

Donors and multilateral development institutions should mainstream and support adaptation across their assistance to developing countries. The international community should also support adaptation through investment in global public goods, including improved monitoring and prediction of climate change, better modelling of regional impacts, and the development and deployment of drought- and flood-resistant crops.

In addition, efforts should be increased to build public-private partnerships for climate-related insurance; and to strengthen mechanisms for improving risk management and preparedness, disaster response and refugee resettlement.

Strong and early mitigation has a key role to play in limiting the long- run costs of adaptation. Without this, the costs of adaptation will rise dramatically.

Building and sustaining collective action is now an urgent challenge.

The key building blocks for any collective action include developing a shared understanding of the long-term goals for climate policy, building effective institutions for co-operation, and demonstrating leadership and working to build trust with others.

Without a clear perspective on the long-term goals for stabilisation of greenhouse gas concentrations in the atmosphere, it is unlikely that action will be sufficient to meet the objective.

Action must include mitigation, innovation and adaptation. There are many opportunities to start now, including where there are immediate benefits and where large-scale pilot programmes will generate valuable experience. And we have already begun to create the institutions to underpin co-operation.

The challenge is to broaden and deepen participation across all the relevant dimensions of action – including co-operation to create carbon prices and markets, to accelerate innovation and deployment of low-carbon technologies, to reverse emissions from land-use change and to help poor countries adapt to the worst impacts of climate change.

There is still time to avoid the worst impacts of climate change if strong collective action starts now.

This Review has focused on the economics of risk and uncertainty, using a wide range of economic tools to tackle the challenges of a global problem which has profound long-term implications. Much more work is required, by scientists and economists, to tackle the analytical challenges and resolve some of the uncertainties across a broad front. But it is already very clear that the economic risks of inaction in the face of climate change are very severe.

There are ways to reduce the risks of climate change. With the right incentives, the private sector will respond and can deliver solutions. The stabilisation of greenhouse gas concentrations in the atmosphere is feasible, at significant but manageable costs.

The policy tools exist to create the incentives required to change investment patterns and move the global economy onto a low-carbon path. This must go hand-in-hand with increased action to adapt to the impacts of the climate change that can no longer be avoided.

Above all, reducing the risks of climate change requires collective action. It requires co-operation between countries, through international frameworks that support the achievement of shared goals. It requires a partnership between the public and private sector, working with civil society and with individuals. It is still possible to avoid the worst impacts of climate change; but it requires strong and urgent collective action. Delay would be costly and dangerous.