Part III
The Economics of Stabilisation

Part III of the Review considers the economic challenges of achieving stabilisation of greenhouse gases in the atmosphere.

'Business as usual' emissions will take greenhouse-gas concentrations and global temperatures way beyond the range of human experience. In the absence of action, the stock of greenhouse gases in the atmosphere could more than treble by the end of the century.

Stabilisation of concentrations will require deep emissions cuts of at least 25% by 2050, and ultimately to less than one-fifth of today's levels. The costs of achieving this will depend on a number of factors, particularly progress in bringing down the costs of technologies. Overall costs are estimated at around 1% of GDP for stabilisation levels between 500-550ppm CO_2e.

The costs will not be evenly felt – some carbon-intensive sectors will suffer, while for others, climate change policy will create opportunities. Climate-change policies may also have wider benefits where they can be designed in a way that also meets other goals.

Comparing the costs and benefits of action clearly shows that the benefits of strong, early action on climate change outweigh the costs. The current evidence suggests aiming for stabilisation somewhere within the range 450-550ppm CO_2e. Ignoring climate change will eventually damage economic growth; tackling climate change is the pro-growth strategy.

Part III is structured as follows:

- **Chapter 7** discusses the past drivers of global emissions growth, and how these are likely to evolve in the future.

- **Chapter 8** explains what needs to happen to emissions in order to stabilise greenhouse-gas concentrations in the atmosphere, and the range of trajectories available to achieve this.

- **Chapter 9** discusses how to identify the costs of mitigation, and looks at a resource-based approach to calculating global costs.

- **Chapter 10** compares modelling approaches to calculating costs, and looks at how policy choices may influence cost.

- **Chapter 11** considers how climate-change policies may affect competitiveness if they are not applied evenly worldwide.

- **Chapter 12** looks at how to take advantage of the opportunities and wider benefits arising from action on climate change.

- **Chapter 13** brings together the analysis of costs and benefits, and looks at how a global long-term goal for climate-change policy can be defined.

Part III: The Economics of Stabilisation

7 Projecting the Growth of Greenhouse-Gas Emissions

Key Messages

Greenhouse-gas concentrations in the atmosphere now stand at around 430ppm CO_2 equivalent, compared with only 280ppm before the Industrial Revolution. The stock is rising, driven by increasing emissions from human activities, including energy generation and land-use change.

Emissions have been driven by economic development. CO_2 emissions per head have been strongly correlated with GDP per head across time and countries. North America and Europe have produced around 70% of CO_2 emissions from energy production since 1850, while developing countries – non-Annex 1 parties under the Kyoto Protocol – account for less than one quarter of cumulative emissions.

Annual emissions are still rising. Emissions of carbon dioxide, which accounts for the largest share of greenhouse gases, grew at an average annual rate of around 2½% between 1950 and 2000. In 2000, emissions of all greenhouse gases were around 42GtCO_2e, increasing concentrations at a rate of about 2.7ppm CO_2e per year.

Without action to combat climate change, atmospheric concentrations of greenhouse gases will continue to rise. In a plausible 'business as usual' scenario, they will reach 550ppm CO_2e by 2035, then increasing at 4½ppm per year and still accelerating.

Most future emissions growth will come from today's developing countries, because of more rapid population and GDP growth than developed countries, and an increasing share of energy-intensive industries. The non-Annex 1 parties are likely to account for over three quarters of the increase in energy-related CO_2 emissions between 2004 and 2030, according to the International Energy Agency, with China alone accounting for over one third of the increase.

Total emissions are likely to increase more rapidly than emissions per head, as global population growth is likely to remain positive at least to 2050.

The relationship between economic growth and development and CO_2 emissions growth is not immutable. There are examples where changes in energy technologies, the structure of economies and the pattern of demand have reduced the responsiveness of emissions to income growth, particularly in the richest countries. Strong, deliberate policy choices will be needed, however, to decarbonise both developed and developing countries on the scale required for climate stabilisation.

Increasing scarcity of fossil fuels alone will not stop emissions growth in time. The stocks of hydrocarbons that are profitable to extract (under current policies) are more than enough to take the world to levels of CO_2 concentrations well beyond 750ppm, with very dangerous consequences for climate-change impacts. Indeed, with business as usual, energy users are likely to switch towards more carbon-intensive coal, oil shales and synfuels, tending to *increase* rates of emissions growth. It is important to redirect energy-sector research, development and investment away from these sources towards low-carbon technologies.

Extensive carbon capture and storage would allow some continued use of fossil fuels, and help guard against the risk of fossil fuel prices falling in response to global climate-change policy, undermining its effectiveness.

7.1 Introduction

Part II showed that continuing climate change will produce harmful and ultimately dangerous impacts on the environment, the global economy and society. This chapter shows that, in the absence of deliberate policy to combat climate change, global greenhouse-gas emissions will continue to increase at a rapid rate.

Even if annual greenhouse-gas (GHG) emissions remained at the current level of 42 $GtCO_2$ equivalent[1] each year[2], the world would experience major climate change. That rate of emissions would be sufficient to take greenhouse-gas concentrations to over 650ppm CO_2 equivalent (CO_2e) by the end of this century, likely to result eventually in a rise in the global mean temperature of at least 3°C from its pre-industrial level[3].

But annual emissions are not standing still – they are rising, at a rapid rate. If they continue to do so, then the outlook is even worse.

This chapter reviews some of the projections of emissions growth in Section 7.2, noting that, despite the uncertainties about the precise pace of increases, there is powerful evidence, robust to plausible variations in the detail of forecasts, that with 'business as usual' emissions will reach levels at which the impacts of climate change are likely to be very dangerous. Sections 7.3 to 7.5 then look behind the headline projections to consider the main drivers of energy-related emissions growth: economic growth, technological choices affecting carbon intensity of energy use and energy intensity of output, and population growth. This is helpful not only in understanding what underlies the projections but also in identifying the channels through which climate-change policy can work. Finally, in Section 7.6, the chapter argues that fossil fuels' increasing scarcity is not going to rein in emissions growth by itself. To the contrary, there will be a problem for climate-change policies if they induce significant falls in fossil-fuel prices. That is one reason why carbon capture and storage technology is so important.

7.2 Past greenhouse-gas emissions and current trends

57% of emissions are from burning fossil fuels in power, transport, buildings and industry; agriculture and changes in land use (particularly deforestation) produce 41% of emissions.

Total greenhouse-gas emissions were 42 $GtCO_2e$[4] in 2000[5], of which 77% were CO_2, 14% methane, 8% nitrous oxide and 1% so-called F-gases such as perfluorocarbon and sulphur hexafluoride. Sources of greenhouse-gas emissions comprise:

- Fossil-fuel combustion for energy purposes in the power, transport, buildings and industry sectors amounted to 26.1 $GtCO_2$ in 2004[6]. Combustion of coal, oil and gas in electricity and heat plants accounted for most of these emissions, followed by transport (of which three quarters is road transport), manufacturing and construction and buildings.
- Land-use change such as deforestation releases stores of CO_2 into the atmosphere.
- Methane, nitrous oxide and F-gases are produced by agriculture, waste and industrial processes. Industrial processes such as the production of cement and chemicals involve a chemical reaction that releases CO_2 and non-CO_2 emissions. Also, the process of

---

[1] Greenhouse gases are converted to a common unit, CO_2 equivalent, which measures the amount of carbon dioxide that would produce the same global warming potential (GWP) over a given period as the total amount of the greenhouse gas in question. In 2000, 77% of the 100-year GWP of *new emissions* was from CO_2. See Table 8.1 for conversion factors for different gases. Figures for the *stock* of greenhouse gases are usually reported in terms of the amount of CO_2 that would have the equivalent effect on current radiative forcing, i.e. they focus on the GWP over one year.

[2] GHG emissions in 2000 were 42 $GtCO_2e$, WRI (2006). This does not include some emissions for which data is unavailable. For example: CO_2 emissions from soil; additional global warming effect of aviation, including the uncertain contrail effect (see Box 15.6); CFCs (for example from refrigerants in developing countries); and aerosols (for example, from the burning of biomass).

[3] Chapter 8 examines the relationship between stabilisation levels, temperatures and emissions trajectories.

[4] WRI (2006).

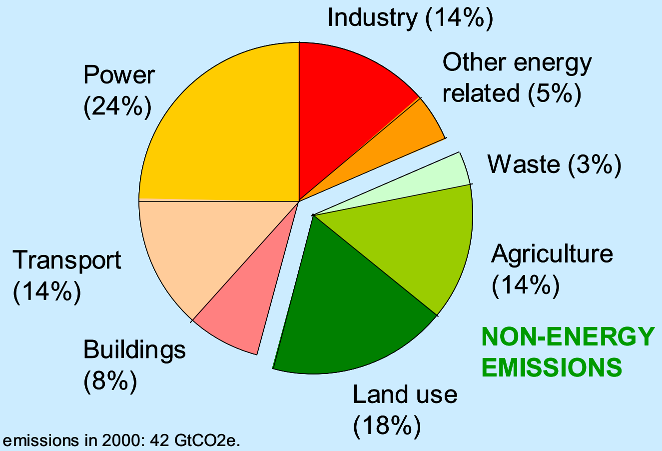
[5] WRI (2006). Historical emission figures are drawn from the WRI's Climate Analysis Indicators Database (CAIT) http://cait.wri.org. Emission estimates exclude: CO_2 emissions from soil; additional global warming effect of aviation, including the uncertain cirrus cloud effect (see Box 15.6); CFCs (for example from refrigerants in developing countries); and aerosols (for example, from the burning of biomass).

[6] IEA (in press).

extracting fossil fuels and making them ready for use generates CO_2 and non-CO_2 emissions (so-called fugitive emissions).

The shares are summarised in Figure 7.1 below, and emissions sources are analysed further by sector in Box 7.1 and Annexes 7.B to 7.G[7].

Figure 7.1 GHG emissions in 2000, by source[8]



Total emissions in 2000: 42 GtCO2e.

Energy emissions are mostly CO_2 (some non-CO_2 in industry and other energy related).
Non-energy emissions are CO_2 (land use) and non-CO_2 (agriculture and waste).

Source: WRI (2006)

Box 7.1 Current and projected emissions sources by sector

Power

A quarter of all global greenhouse-gas emissions come from the generation of power and heat, which is mostly used in domestic and commercial buildings, and by industry. This was the fastest growing source of emissions worldwide between 1990 and 2002, growing at a rate of 2.2% per year; developing-country emissions grew most rapidly, with emissions from Asia (including China and India), the Middle East and the transition economies doubling between 1990 and 2000.

This sector also includes emissions arising from petroleum refineries, gas works and coal mines in the transformation of fossil fuel into a form that can be used in transport, industry and buildings. Emissions from this source are likely to increase over four-fold between now and 2050 because of increased synfuel production from gas and coal, according to the IEA. Total power-sector emissions are likely to rise more than three-fold over this period. For more detail on power emissions, see Annex 7.B.

Land use

Changes in land use account for 18% of global emissions. This is driven almost entirely by emissions from deforestation. Deforestation is highly concentrated in a few countries. Currently around 30% of land-use emissions are from Indonesia and a further 20% from Brazil.

Land-use emissions are projected to fall by 2050, because it is assumed that countries stop deforestation after 85% of forest has been cleared. For more detail, see Annex 7.F.

---

[7] For Annexes 7B to 7G see www.sternreview.org.uk

[8] Emissions are presented according to the sector from which they are directly emitted, i.e. emissions are by source, as opposed to end user/activity; the difference between these classifications is discussed below.

Agriculture

Non-CO_2 emissions from agriculture amount to 14% of total GHG emissions. Of this, fertiliser use and livestock each account for one third of emissions; other sources include rice and manure management. Over half of these emissions are from developing countries. Agricultural practices such as the manner of tillage are also responsible for releasing stores of CO_2 from the soil, although there are no global estimates of this effect. Agriculture is also indirectly responsible for emissions from land-use change (agriculture is a key driver of deforestation), industry (in the production of fertiliser), and transport (in the movement of goods). Increasing demand for agricultural products, due to rising population and incomes per head, is expected to lead to continued rises in emissions from this source. For more detail on trends in agriculture emissions, see Annex 7.G.

Total non-CO_2 emissions are expected to double in the period to 2050[9].

Transport

Transport accounts for 14% of global greenhouse-gas emissions, making it the third largest source of emissions jointly with agriculture and industry. Three-quarters of these emissions are from road transport, while aviation accounts for around one eighth and rail and shipping make up the remainder. The efficiency of transport varies widely between countries, with average efficiency in the USA being around two thirds that in Europe and half that in Japan[10]. Total CO_2 emissions from transport are expected to more than double in the period to 2050, making it the second-fastest growing sector after power.

CO_2 emissions from aviation are expected to grow by over three-fold in the period to 2050, making it among the fastest growing sectors. After taking account of the additional global warming effects of aviation emissions (discussed in Box 15.8), aviation is expected to account for 5% of the total warming effect (radiative forcing) in 2050[11]. For more detail on trends in transport emissions, see annex 7.C.

Industry

Industry accounts for 14% of total direct emissions of GHG (of which 10% are CO_2 emissions from combustion of fossil fuels in manufacturing and construction and 3% are CO_2 and non-CO_2 emissions from industrial processes such as production of cement and chemicals).

Buildings

A further 8% of emissions are accounted for by direct combustion of fossil fuels and biomass in commercial and residential buildings, mostly for heating and cooking.

The contribution of the buildings and industry sectors to climate change are greater than these figures suggest, because they are also consumers of the electricity and heat produced by the power sector (as shown in Figure B below). Direct emissions from both industry and buildings are both expected to increase by around two thirds between 2000 and 2050 under BAU conditions. For more detail on industry and buildings emissions, see Annex 7.D and 7.E respectively.

---

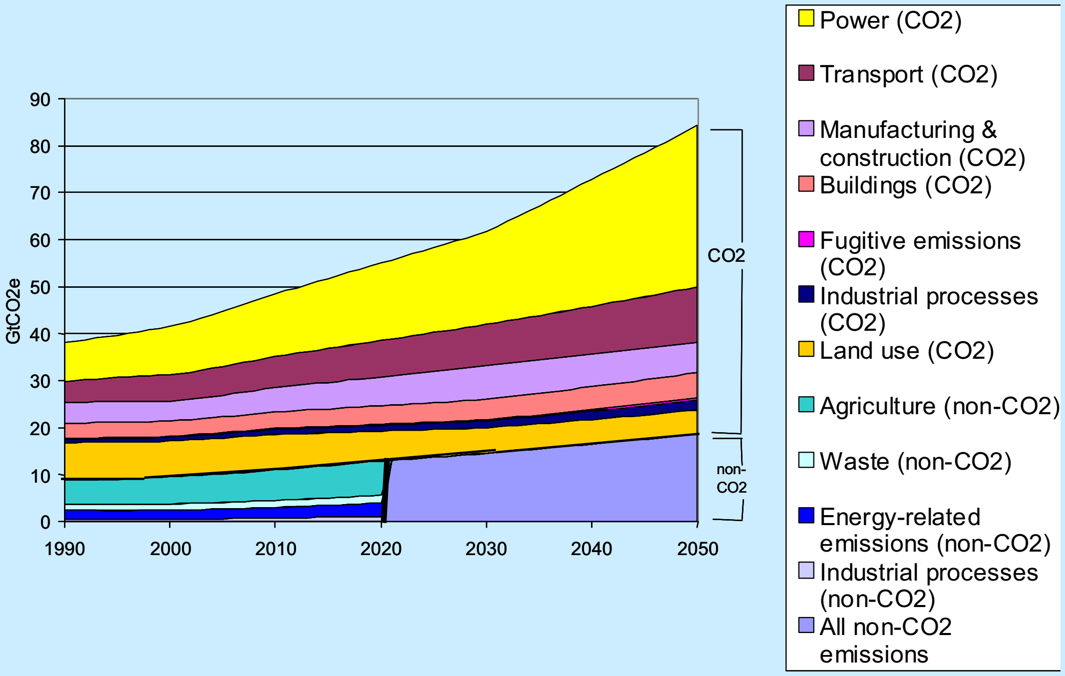
[9] There are no projections available splitting non-CO_2 emission estimates into individual sector sources after 2020.

[10] An and Sauer (2004).

[11] For explanation of how these percentages are calculated, see Box 15.6. The transport emissions presented in Figure A and B include CO_2 emissions from aviation, but exclude the additional global warming effect of these emissions at altitude because there is no internationally agreed consensus on how to include these effects.

[12] Note the estimates of energy-related CO_2 emissions in the early 1990s include approximate estimates of emissions from transition economies, which are sometimes excluded from data tables from the WRI (2006).

Figure A Historical and projected GHG emissions by sector (by source)



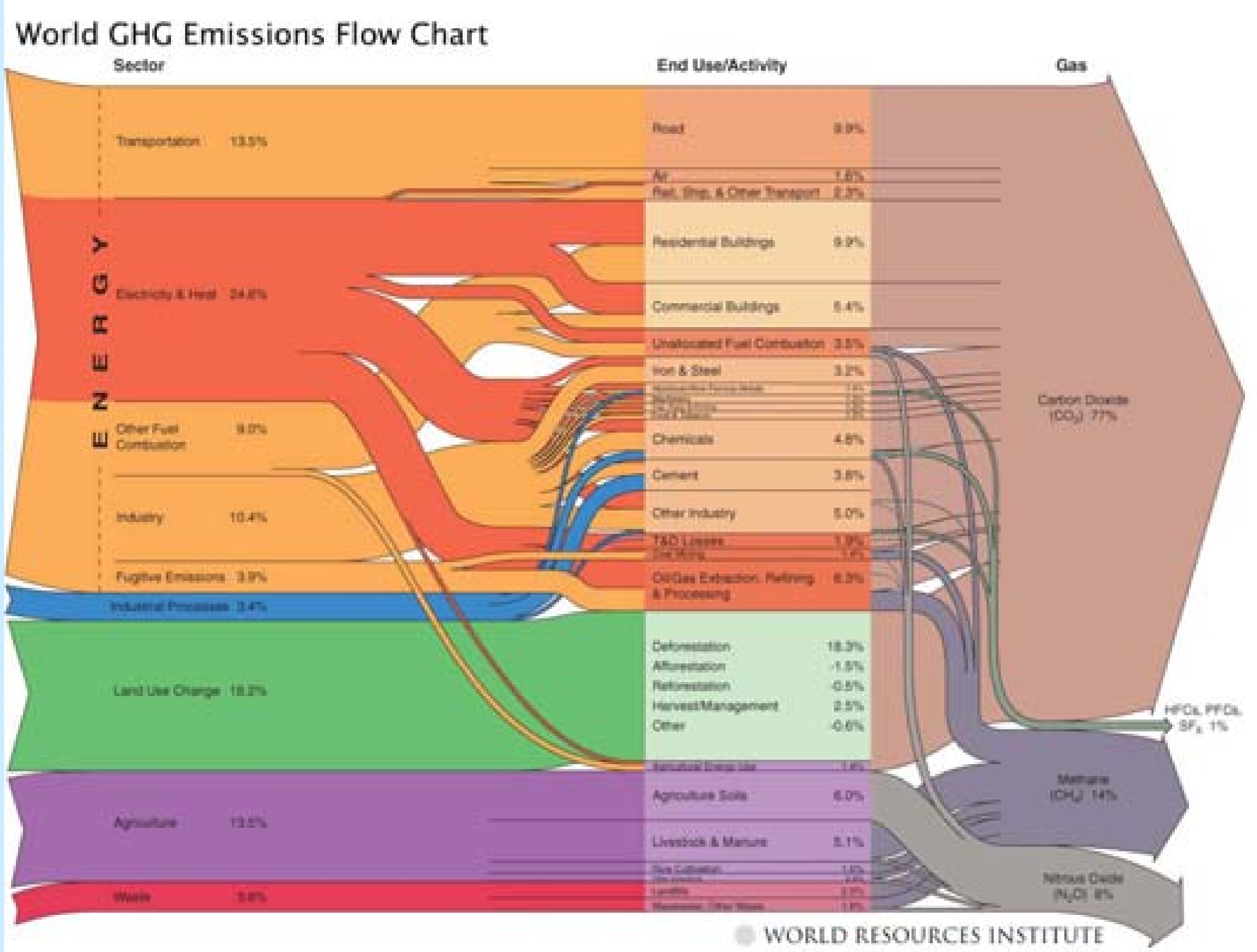
Source: WRI (2006), IEA (in press), IEA (2006), EPA (forthcoming), Houghton (2005).

GHG emissions can also be classified according to the activity associated with them. Figure B below shows the relationship between the physical source of emissions and the end use/activity associated with their production. For example, at the left-hand side of the diagram it can be seen that electricity generation leads to production of emissions at the coal, gas or oil plant; the electricity produced is then consumed by residential and commercial buildings and in a range of industries such as chemicals and aluminium.

This analysis is useful for building a detailed understanding of the drivers behind emissions growth and how emissions can be cut. For example, emissions from the power sector can be cut either by improving the efficiency and technology of the power plant, or by reducing the end-use demand for electricity.

Data sources for historical and projected GHG emissions used in this box and throughout the report:
Historical data on all GHG emissions (1990-2002) from WRI (2006)[12].
Fossil-fuel emissions projections (i.e. power, transport, buildings and industry CO_2 emissions) from IEA. Data for 2030 taken from IEA (in press) and data for 2050 from IEA (2006). Intermediate years calculated by extrapolation.
Land-use emission projections were taken from Houghton (2005).
Non-CO_2 emission projections to 2020 from EPA (forthcoming). Figures extrapolated to 2050 using IPCC SRES scenarios A1F1 and A2.
CO_2 industrial-process and CO_2 fugitive emissions projections extrapolated at 1.8% pa (the growth rate in fossil fuel emissions anticipated by the IEA).

Figure B World Resources Institute mapping from sectors to greenhouse-gas emissions



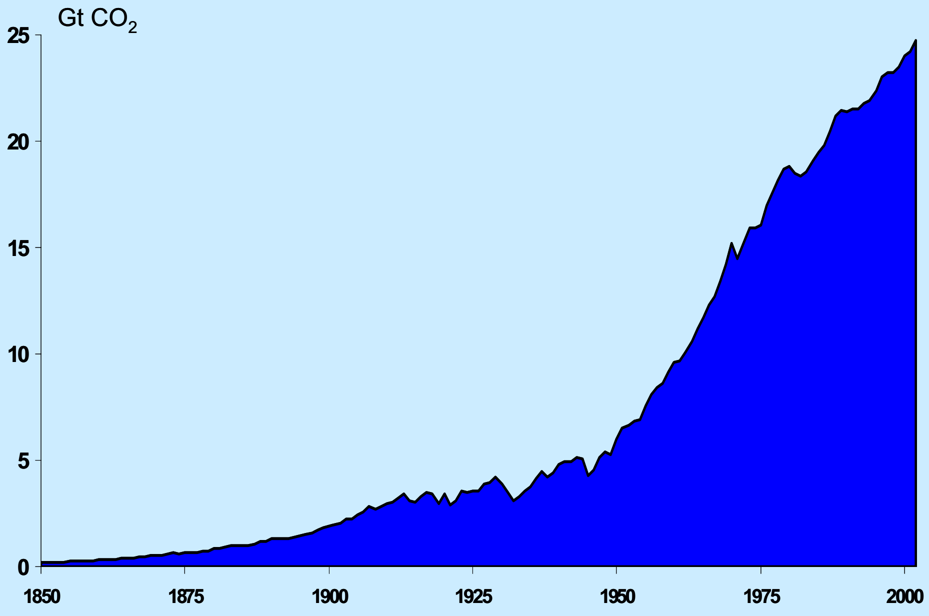
Annual global greenhouse-gas emissions have been growing.

Figure 7.2 illustrates the long-run trend of energy-related CO_2 emissions[13], for which reasonable historical data exist. Between 1950 and 2002, emissions rose at an average annual rate of over 3%. Emissions from burning fossil fuels for the power and transport sectors have been increasing since the mid-nineteenth century, with a substantial acceleration in the 1950s.

The rate fell back somewhat in the three decades after 1970, but was still 1.7% on average between 1971 and 2002 (compared with an average rate of increase in energy demand of 2.0% per year). The slowdown appears to have been associated with the temporary real increases in the price of oil in the 1970s and 1980s, the sharp reduction in emissions in Eastern Europe and the former Soviet Union due to the abrupt changes in economic systems in the 1990s, and increases in energy efficiency in China following economic reforms.

The majority of emissions have come from rich countries in the past. North America and Europe have produced around 70% of the CO_2 from energy production since 1850, while developing countries – non-Annex 1 parties under the Kyoto Protocol – account for less than one quarter of cumulative emissions.

Figure 7.2 Global CO_2 emissions from fossil-fuel burning and cement over the long term



Source: Climate Analysis Indicators Tool (CAIT) Version 3.0. (Washington, DC: World Resources Institute, 2006)

Less is known about historical trends in emissions from agriculture and changes in land use, but emissions due to land-use changes and deforestation are thought to have risen on average by around 1.5% annually between 1950 and 2000, according to the World Resources Institute.

In total, between 1990 and 2000 (the period for which comprehensive data are available), the average annual rate of growth of non-CO_2 greenhouse gases, in CO_2-equivalent terms, was 0.5% and of all GHGs together 1.2%.

---

[13] Including emissions from international aviation and shipping and CO_2 emissions from the industrial process of making cement.

Global emissions are projected to continue to rise in the absence of climate-change policies; 'business as usual' will entail continuing increases in global temperatures well beyond levels previously experienced by humankind.

Some simple arithmetic can illustrate this. The concentration of greenhouse gases in the atmosphere is currently at around 430ppm CO_2e, adding 2-3ppm a year. Emissions are rising. But suppose they continue to add to GHG concentrations by only 3ppm a year. That will be sufficient to take the world to 550ppm in 40 years and well over 700ppm by the end of the century. Yet a stable global climate requires that the stock of greenhouse gases is constant and therefore that emissions are brought down to the level that the Earth system can naturally absorb from the atmosphere annually in the long run.

Formal projections suggest that the situation in the absence of climate-change policies is worse than in this simple example. The reference scenario[14] in the International Energy Agency (IEA)'s 2006 World Energy Outlook projects an increase of over 50% in annual global fossil fuel CO_2 emissions between 2004 and 2030, from 26 $GtCO_2$ to 40 $GtCO_2$, an annual average rate of increase of 1.7%. The reference scenario for the IEA's Energy Technology Perspectives envisages emissions of 58 $GtCO_2$ by 2050.

Developing countries will account for over three-quarters of the increase in fossil-fuel emissions to 2030, according to the World Energy Outlook, thanks to rapid economic growth rates and their growing share of many energy-intensive industries. China may account for over one third of the increase by itself, with Chinese emissions likely to overtake those of the United States by the end of this decade, driven partly by heavy use of coal.

The fastest growing sectors are driven by growth in demand for transport. The second fastest source of emissions is expected to be aviation, expected to rise about three-fold over the same period. Fugitive emissions are expected to increase over four-fold in the period to 2050, because of an increase in production of synfuels from gas and coal, mostly for use in the transport sector.

Other 'business as usual' (BAU) projections show similar patterns. The US Energy Information Administration is currently projecting an increase from 25 $GtCO_2$ in 2003 to 43.7 $GtCO_2$ by 2030, at an annual average rate of increase of 2.1%[15], as does the POLES model[16]. The factors responsible for the rise in energy-related missions are considered further in the sections below.

Projections of future emissions from land-use changes remain uncertain. At the current rate of deforestation, most of the top ten deforesting nations would clear their forests before 2100. Based on rates of deforestation over the past two decades, and assuming that countries stop deforestation when 85% of the forests they had in 2000 have been cut down, annual emissions will remain at around 7.5 $GtCO_2$/yr until 2012, falling to 5 $GtCO_2$/yr by 2050 and 2 $GtCO_2$/yr by 2100[17].

The US Environmental Protection Agency (EPA) projects an increase in agricultural emissions from 5.7 to 7.3 $GtCO_2e$ between 2000 and 2020 with business as usual. The key drivers behind agricultural emissions growth are population and income growth. While the share of emissions from the OECD and transition economies is expected to fall, the share from developing countries is expected to increase, especially in Africa and Latin America. The income elasticity of demand for meat is often high in developing countries, which will tend to raise emissions from livestock. Increases in emissions from other sources, including waste and industrial processes, are also expected.

---

[14] The reference scenario assumes no major changes to existing policies.

[15] Different modellers may use slightly different definitions of emissions, depending on their treatment of international marine and aviation fuel bunkers and gas flaring.

[16] According to WRI (2006).

[17] Houghton (2005)

Looking at emissions from all sources together, the IPCC Special Report on Emissions Scenarios, published in 2000, considered a wide range of possible future scenarios. Although they differ considerably, all entail substantial increases in emissions for at least the next 25 years and increases in greenhouse-gas concentrations at least until the end of the century. All but one SRES storyline envisage a concentration level well in excess of 650ppm CO_2e by then. Academic studies also envisage steady increases. The MIT EPPA model reference projection, for example, envisages an average annual increase in CO_2 emissions of 1.26% between 1997 and 2100 (faster in the earlier years). In the rest of the report, for the purposes of illustrating the size of the emission abatement required to achieve various CO_2e concentration levels, a BAU trajectory based on IEA, EPA, IPCC and Houghton projections has been used[18]. This is broadly representative of BAU projections in the literature and results in emissions reaching 84 $GtCO_2e$ per year, and a greenhouse-gas level of around 630ppm CO_2e, by 2050.

Despite the differences across the emissions scenarios in the literature and the unavoidable uncertainty in making long-run projections, any plausible BAU scenario entails continuing increases in global temperatures, well beyond levels previously experienced by humankind, with the profound physical, social and economic consequences described in Part II of the Review. If, for instance, the average annual increase in greenhouse-gas emissions is 1.5%[19], concentrations will reach 550ppm CO_2e by around 2035, by when they will be increasing at 4½ppm per year and still accelerating.

The rest of this chapter takes a more detailed look at the drivers that lie behind these headline projections.

7.3 The determinants of energy-related CO_2 emissions

The drivers of emissions growth can be broken down into different components.

The reasons why annual emissions are projected to increase under ‘business as usual’ can be better understood by focusing on energy-related CO_2 emissions from the combustion of fossil fuel, which have been more thoroughly investigated than emissions from land use, agriculture and waste[20].

The so-called Kaya identity expresses total CO_2 emissions in terms of the components of an accounting identity: the level of output (which can be further split into population growth and GDP per head); the energy intensity of that output; and the carbon intensity of energy[21]:

$$\text{CO}_2 \text{ emissions from energy} \equiv \text{Population} \times (\text{GDP per head}) \times (\text{energy use/GDP}) \times (\text{CO}_2 \text{ emissions/energy use})$$

Trends in each of these components can then be considered in turn. In particular, it can immediately be seen that increases in world GDP will tend to increase global emissions, unless income growth stimulates an offsetting reduction in the carbon intensity of energy use or the energy intensity of GDP.

Table 7.1 abstracts from the impact of population size and focuses on emissions per head, which are equal to the product of income per head, carbon intensity of energy and energy intensity. These are reported for the world and various countries and groupings within it. The table

---

[18] Fossil fuel projections to 2050 are taken from IEA (2006). Non-CO_2 emission projections to 2020 are taken from EPA (forthcoming) and extrapolated forward to 2050 in a manner to be consistent with non-CO_2 emissions reached by SRES scenarios A1F1 and A2. Land use emissions to 2050 are taken from Houghton (2005). Actual estimates of CO_2 emissions from industrial processes and CO_2 fugitive emissions were taken from CAIT until 2002; henceforth, they are extrapolated at 1.8% pa (the average growth rate for fossil fuel emissions projected by IEA).

[19] This assumes that total emissions of greenhouse gases grow more slowly than emissions of CO_2. Their annual growth rate was about 0.5 percentage points lower during 1990 to 2000.

[20] Econometric studies of past data have tended to focus on energy-related CO_2 emissions, although modellers are increasingly including non-CO_2 GHGs in their projections. See, for example, Paltsev et al. (2005).

[21] Kaya (1990)

illustrates the wide variation in emissions per head across countries and regions, and how this variation is driven primarily by variations in income per head and, to a lesser extent, by variations in energy intensity. It also illustrates the similarity in the carbon intensity of energy across countries and regions.

Table 7.1 Key ratios for energy-related[22] CO_2 emissions in 2002

Country/grouping	CO_2 per head (tCO_2)	GDP per head ($ppp2000)	CO_2 emissions/energy use (tCO_2/toe)	Energy use/GDP (toe/$ppp2000 x 10^6)
USA	20.4	34430	2.52	230.8
EU	9.4	23577	2.30	158.0
UK	9.6	27176	2.39	140.6
Japan	9.8	26021	2.35	155.7
China	3.0	4379	3.08	219.1
India	1.1	2555	2.05	201.3
OECD	11.7	24351	2.41	193.0
Economies in transition	7.7	7123	2.57	421.2
Non-Annex 1 parties	2.2	3870	2.48	217.8
World	4.0	7649	2.43	219.5

Source: WRI (2006).

Some of the factors determining these ratios change only very slowly over time. Geographers have drawn attention to the empirical importance of a country's endowments of fossil fuels and availability of renewable energy sources[23], which appear to affect both the carbon intensity of energy use and energy use itself. Qatar, a Gulf oil-producing state, for example, has the highest energy use per head and the highest CO_2 emissions per head[24]. China, which uses a greater proportion of coal in its energy mix than the EU, has a relatively high figure for carbon intensity. A country's typical winter climate and population density are also important influences on the energy intensity of GDP.

But some factors are subject to change. Economists have stressed, for example, the role of the prices of different types of energy, the pace and direction of technological progress, and the structure of production in different countries in influencing carbon intensity and energy intensity[25].

Falls in the carbon intensity of energy and energy intensity of output have slowed the growth in global emissions, but total emissions have still risen, because of income and population increases.

In Table 7.2, the Kaya identity is used to break down the total growth rates of energy-related CO_2 emissions for various countries and regions over the period 1992 to 2002 into the contributions – in an accounting sense – from population growth, changes in the carbon intensity of energy use, changes in the energy intensity of GDP, and growth of GDP per head. It shows that, in the recent past, income growth per head has tended to raise global emissions (by 1.9% per year) whereas reductions in global carbon and energy intensity have tended to reduce them (by the same amount). Because world population has grown (by 1.4% per year), emissions have gone up.

---

[22] Energy-related emissions include all fossil-fuel emissions plus CO_2 emissions from industrial processes.

[23] E.g. Neumayer (2004)

[24] Generous endowments of raw materials are not necessarily reflected in domestic consumption (e.g. South Africa and diamonds), but in the case of energy there does seem to be a significant correlation, perhaps because of the broad-based demand for energy and the tendency for local energy prices to be relatively low in energy-rich countries.

[25] E.g. Huntington (2005) and McKibbin and Stegman (2005)

Table 7.2 Annual growth rates in energy related[26] CO_2 emissions and their components, 1992-2002 (%)					
Country/grouping	CO_2 emissions ($GtCO_2$)	GDP per head	Carbon intensity	Energy intensity	Population
USA	1.4	1.8	0.0	-1.5	1.2
EU	0.2	1.8	-0.7	-1.2	0.3
UK	-0.4	2.4	-1.0	-2.3	0.2
Japan	0.7	0.7	-0.5	0.2	0.3
China	3.7	8.5	0.5	-6.4	0.9
India	4.3	3.9	1.1	-2.5	1.7
OECD	1.2	1.8	-0.3	-1.1	0.7
Economies in transition	-3.0	0.4	-0.6	-2.7	-0.1
Non-Annex 1 parties	3.3	3.5	0.2	-2.0	1.6
World	**1.4**	**1.9**	**-0.1**	**-1.7**	**1.4**

Source: WRI (2006).

There has been a variety of experience across countries. The EU and the economies in transition were able to reduce carbon intensity considerably during the period, but there was a significant increase in India, from a very low base. Population growth, as well as increases in GDP per head, was particularly important in developing countries. The reductions in the energy intensity of output in China, India and the economies in transition are striking. If energy intensity had fallen in China only at the speed it fell in the OECD, global emissions in 2002 would have been over 10% higher. But Table 7.1 shows that, at least in China and India, energy intensity is now below that of the United States. Economic reforms helped to reduce wasteful use of energy in many countries in the 1990s, but many of the improvements are likely to have reflected catching up with best practice, boosting the level of energy efficiency but not necessarily bringing reductions in its long-run growth rate.

7.4 The role of growth in incomes and population in driving emissions

In the absence of policies to combat climate change, CO_2 emissions are likely to rise as the global economy grows.

Historically, economic development has been associated with increased energy consumption and hence energy-related CO_2 emissions per head. Across 163 countries, from 1960 to 1999, the correlation between CO_2 emissions per head and GDP per head (expressed as natural logarithms) was nearly 0.9[27]. Similarly, one study for the United States estimated that, over the long term, a 1% rise in GDP per head leads to a 0.9% increase in emissions per head, holding other explanatory factors constant[28].

Consistent with this, emissions per head are highest in developed countries and much lower in developing countries – although developing countries are likely to be closing the gap, because of their more rapid collective growth and their increasing share of more energy-intensive industries, as shown in the example of the projection in Figure 7.3[29].

---

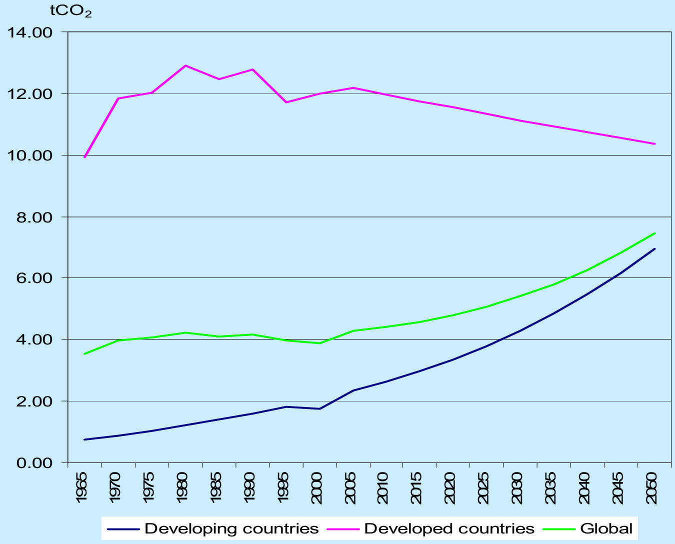
[26] Energy-related emissions include all fossil-fuel emissions plus CO_2 emissions from industrial processes.

[27] See Neumayer, (2004)

[28] See Huntington (2005). GDP per head is itself a function of many other variables, and emissions projections should in principle be based upon explicit modelling of the sources of growth; for example, the consequences for emissions will be different if growth is driven by innovations in energy technology rather than capital accumulation.

[29] Holtsmark, B (2006). McKitrick and Strazicich (2005) have pointed out that global emissions per head behave as a stationary series subject to structural breaks. But this does not preclude increases in global emissions per head in future, either because of structural changes within economies, or changes in the distribution of emissions across fast- and slow-growing economies, leading to further structural breaks.

Figure 7.3 Global emissions per head: history and extrapolations

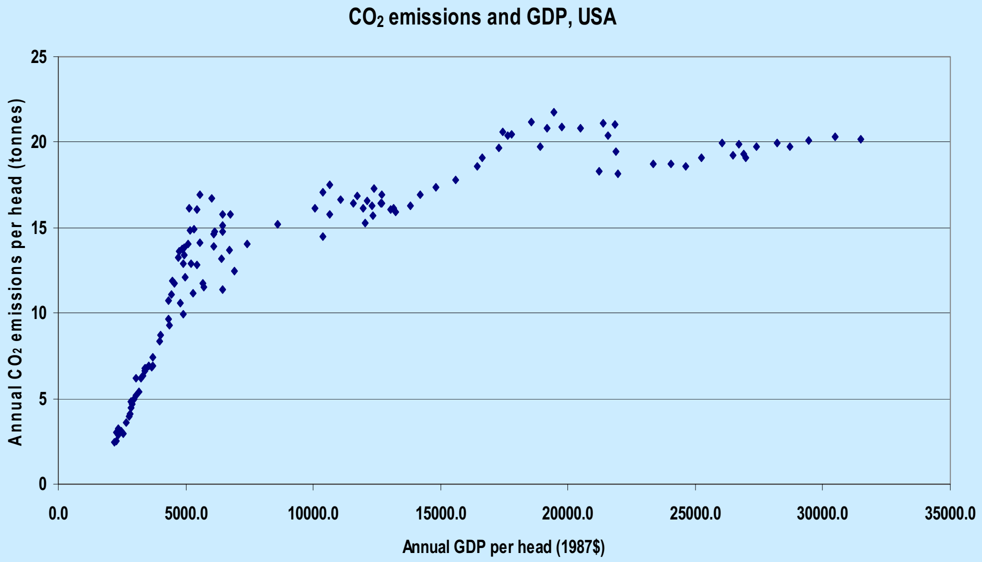


Source: Holtsmark (2006)

Structural shifts in economies may change the relationship between income and emissions.

Structural changes in economies will have a significant impact on their emissions. In some rich countries, the shift towards a service-based economy has helped to slow down, or even reverse, the growth in national emissions. Indeed, emissions per head have fallen in some countries over some periods (e.g. they peaked in the United Kingdom in 1973 and fell around 20% between then and 1984). Holtsmark's extrapolation in Figure 7.3 envisages a decline in emissions per head for the developed world as a whole. And breaks in the relationship between emissions per head and GDP per head have taken place, as seen in Figure 7.4 for the USA, at income levels around $6000 per head, $12000 per head and $22000 per head.

Figure 7.4 Annual emissions of CO_2 per head vs. GDP per head, USA



Source: Huntington (2005)

If it were true that the relationship between emissions and income growth disappeared at higher income levels, emissions growth would eventually be self-limiting, reducing the need to take action on climate change if this happened fast enough. The observation that, at high incomes, some kinds of pollution start to fall is often explained by invoking the 'environmental Kuznets curve' hypothesis – see Annex 7.A. The increasing importance of the 'weightless economy' in the developed world[30], with a rising share of spending accounted for by services, shows how patterns of demand, and the resulting energy use, can change.

However, in the case of climate change, the hypothesis is not very convincing, for three reasons. First, at a global level, there has been little evidence of large voluntary reductions in emissions as a result of consumers' desire to reduce emissions as they become richer. That may change as people's understanding of climate-change risks improves, but the global nature of the externality means that the incentive for uncoordinated individual action is very low. Second, the pattern seen in Figure 7.4 partly reflects the relocation of manufacturing activity to developing countries. So, at the global level, the structural shift within richer countries has less impact on total emissions. Third, demand for some carbon-intensive goods and services – such as air transport[31] – has a high income elasticity, and will continue to grow as incomes rise. Demand for car transport in many developing countries, for example, is likely to continue to increase rapidly. For these reasons, at the global level, in the absence of policy interventions, the long-run positive relationship between income growth and emissions per head is likely to persist. Breaking the link requires significant changes in preferences, relative prices of carbon-intensive goods and services and/or breaks in technological trends. But all of these are possible with appropriate policies, as Part IV of this Review argues.

Different assumptions about the definition and growth of income produce different projections for emissions, but this does not affect the conclusion that emissions are well above levels consistent with a stable climate and are likely to remain so under 'business as usual'.

---

[30] Quah (1996)

[31] Air transport is particularly problematic given its impacts on the atmosphere over and above the simple CO_2 effect. The additional global warming effect of aviation is discussed in Box 15.8.

Projected trajectories for CO_2 are sensitive to long-run growth projections, but the likelihood of economic growth slowing sufficiently to reverse emissions growth by itself is small. Most models assume some decline in world growth rates in the medium to long run, as poorer countries catch up and exhaust the growth possibilities from adopting best practices in production techniques. But some go further and assume that developed-country income growth per head will actually decline. There is no strong empirical basis for this assumption. Neither is the assumption very helpful if one wishes to assess the consequences if developed economies do manage to continue to grow at post-World War II rates.

The choice of method for converting the incomes of different countries into a common currency to allow them to be aggregated also makes some difference – see Box 7.2. But given that the growth rate of global GDP was around 2.9% per year on average between 1900 and 2000, and 3.9% between 1950 and 2000, projecting world growth to continue at between 2 and 3% per year (as in the IPCC SRES scenarios, for example) does not seem unreasonable.

Box 7.2 Using market exchange rates or purchasing power parities in projections

There has been some controversy over how GDPs of different countries and regions should be compared for the purposes of making long-run emissions projections. Some method is required to convert data compiled in national currency terms into a common unit of account. Most emissions scenarios have used market exchange rates (MER), while others have argued for purchasing power parity (PPP) conversions. Castles and Henderson (2003) argue that "the mistaken use of MER-based comparisons, together with questionable assumptions about 'closing the gap' between rich countries and poor, have imparted an upward bias to projections of economic growth in developing countries, and hence to projections of total world emissions."

MER conversions suffer from two main problems. First, although competition tends to equalise the prices of internationally traded goods and services measured in a common currency using MERs, this is not true of non-traded goods and services. As the price of the latter relative to traded goods and services tends to be higher in rich countries than in poor ones, rich countries tend to have higher price levels converted at MERs. This phenomenon arises because the productivity differential between rich and poor countries tends to be larger for traded than non-traded goods and services (the 'Balassa-Samuelson' effect[32]). In this sense, the ratio of income per head between rich countries and poor countries is exaggerated if the comparison is intended to reflect purchasing power. Thus, the use of MERs will mean that developing countries' current GDP levels per head will be underestimated. If GDP levels per head are assumed to converge over some fixed time horizon, this means that the growth rates of the poor countries while they 'catch up' will be exaggerated. Henderson and Castles were concerned that this would lead to an over-estimate of the growth of emissions as well.

Second, MERs can be driven away from the levels that ensure the 'law of one price' for traded goods and services by movements across countries' capital accounts. Different degrees of firms' market power in different countries may also have this effect.

Instead of using MERs, one can try to use conversions based on purchasing power parity (PPP). These try to compare real incomes across countries by comparing the ability to purchase a standard basket of goods and services. But PPP exchange rates have their own problems, as explained by McKibbin et al (2004). PPP calculation requires detailed information about the prices in national currencies of many comparable goods and services. The resource costs are heavy. There are different ways of weighting individual countries' prices to obtain 'international prices' and aggregating volumes of output or expenditure. Different PPP conversions are needed for different purposes. For example, different baskets of products and PPP conversion rates are appropriate for comparing the incomes of old people across countries than for comparing the incomes of the young; similarly, different price indices need to be used for comparing industrial outputs. Data are only available for benchmark years, unlike MERs, which for many countries are available at high frequency.

---

[32] See, for example, Balassa (1964)

But efforts are under way to improve the provision of PPP data. The International Comparison Programme (ICP), launched by the World Bank when Nicholas Stern was Chief Economist, is the world's largest statistical initiative, involving 107 countries and collaboration with the OECD, Eurostat and National Statistical Offices. It produces internationally comparable price levels, economic aggregates in real terms, and Purchasing Power Parity (PPP) estimates that inform users about the relative sizes of markets, the size and structure of economies, and the relative purchasing power of currencies.

In the IPCC SRES scenarios that use MER conversions, it is not clear that the use of MERs biases upwards the projected rates of emissions growth, as the SRES calibration of the past relationship between emissions per head and GDP per head also used GDPs converted at MERs as the metric for economic activity (Holtsmark and Alfsen (2003)). Hence the scenarios are based on a lower estimate of the elasticity of emissions growth per head with respect to (the incorrectly measured) GDP growth per head. As Nakicenovic et al (2003) have argued, the use of MERs in many of the IPCC SRES scenarios is unlikely to have distorted the emissions trajectories much.

Overall, the statement that, under business as usual, global emissions will be sufficient to propel greenhouse-gas concentrations to over 550ppm CO_2e by 2050 and over 650-700ppm by the end of this century is robust to a wide range of changes in model assumptions. It is based on a conservative assumption of constant or very slowly rising annual emissions. The proposition does not, for example, rely on convergence of growth rates of GDP per head across countries, an assumption commonly made in global projections. Cross-country growth regressions suggest that on average there has been a general tendency towards convergence of growth rates[33]. But there has been a wide range of experience over time and regions, and some signs of divergence in the 1990s[34].

Total emissions are likely to increase more rapidly than emissions per head.

The UN projects world population to increase from 6.5 billion in 2005 to 9.1 billion in 2050 in its medium variant and still to be increasing slowly then (at about 0.4% per year), despite projected falls in fertility[35]. The average annual growth rate from 2005 to 2050 is projected to be 0.75%; the UN's low and high variants give corresponding rates of 0.38% and 1.11%. Population growth rates will be higher among the developing countries, which are also likely in aggregate to have more rapid emissions growth per head. This means that emissions in the developing world will grow significantly faster than in the developed world, requiring a still sharper focus on emissions abatement in the larger economies like China, India and Brazil.

Climate change itself is also likely to have an impact on energy demand and hence emissions, but the direction of the net impact is uncertain. Warmer winters in higher latitudes are likely to reduce energy demand for heating[36], but the hotter summers likely in most regions are likely to increase the demand for refrigeration and air conditioning[37].

7.5 The role of technology and efficiency in breaking the link between growth and emissions

The relationship between economic development and CO_2 emissions growth is not immutable.

Historically, there have been a number of pervasive changes in energy systems, such as the decline in steam power, the spread of the internal combustion engine and electrification. The

---

[33] Bosworth, B, and Collins, S (2003)
[34] See McKibbin and Stegman, op. cit.; Pritchett, L (1997)
[35] Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat (2005)
[36] See Neumayer, op. cit.
[37] Asadoorian et al (2006)

adoption of successive technologies changed the physical relationship between energy use and emissions. A number of authors have identified in several countries structural breaks in the observed relationship that are likely to have been the result of such switches[38]. Using US data, Huntington (2005) found that, after allowing for these technology shifts, the positive relationship between emissions per head and income per head has remained unchanged, casting some doubt on the scope for changes in the structure of demand to reduce emissions in the absence of deliberate policy. Also, an MIT study suggests that, since 1980, changes in US industrial structure have had little effect on energy intensity[39].

Shifts usually entailed switching from relatively low-energy-density fuels (e.g. wood, coal) to higher-energy-density ones (e.g. oil), and were driven primarily by technological developments, not income growth (although cause and effect are difficult to disentangle, and changes in the pattern of demand for goods and services may also have played a role). The energy innovations and their diffusion were largely driven by their advantages in terms of costs, convenience and suitability for powering new products (with some local environmental concerns, such as smog in London or Los Angeles, occasionally playing a part). As the discussion of technology below suggests (see Chapter 16), given the current state of knowledge, alternative technologies do not appear, on balance, to have the inherent advantages over fossil-fuel technologies (e.g. in costs, energy density or suitability for use in transport) necessary if decarbonisation were to be brought about purely by private commercial decisions. Strong policy will therefore be needed to provide the necessary incentives.

Technical progress in the energy sector and increased energy efficiency are also likely to moderate emissions growth. Figure 7.5, for instance, illustrates that the efficiency with which energy inputs are converted into useful energy services in the United States has increased seven-fold in the last century. One study has found that innovations embodied in information technology and electrical equipment capital stocks have played a key part in reducing energy intensity over the long term[40]. But, in the absence of appropriate policy, incremental improvements in efficiency alone will not overwhelm the income effect. For example, a review of projections for China carried out for the Stern Review suggests that energy demand is very likely to increase substantially in ‘business as usual’ scenarios, despite major reductions in energy intensity[41]. And in the USA, emissions per head are projected to rise whenever income per head grows at more than 1.8% per year[42]. But the scale of potential cost-effective energy efficiency improvements, which will be explored elsewhere in this Review, indicates that energy efficiency and reductions in energy intensity constitute an important and powerful part of a wider strategy.

---

[38] See, for example, Lanne and Liski (2004) and Huntington, op. cit. The former study 16 countries but use a very limited set of explanatory variables.

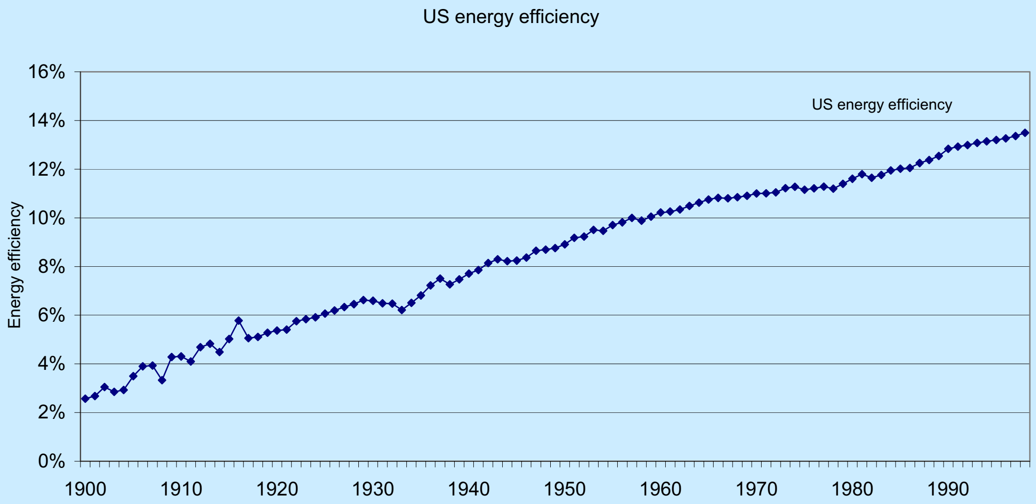
[39] Sue Wing and Eckaus (2004)

[40] Sue Wing and Eckaus (2004)

[41] Understanding China’s Energy Policy: Background Paper Prepared for Stern Review on the Economics of Climate Change by the Research Centre for Sustainable Development, Chinese Academy of Social Sciences

[42] Huntington, op. cit.

Figure 7.5 Energy conversion efficiencies, USA, 1900–1998



Source: Ayres et al (2005) and Ayres and Warr (2005) This graph shows the efficiency with which power from fossil-fuel, hydroelectric and nuclear sources is converted into useful energy services. The percentages reflect the ratio of useful work output to energy input.

Chapter 9 will set out in more detail the potential for improvements in efficiency and technology; Part IV of this report will look at how policy frameworks can be designed to make this happen.

7.6 The impact of fossil-fuel scarcity on emissions growth

This chapter has argued that, without action on climate change, economic growth and development are likely to generate levels of greenhouse-gas emissions that would be very damaging. Development is likely to lead to increasing demand for fossil-fuel energy, and, without appropriate international collective action, producers and consumers will not modify their behaviour to reduce the adverse impacts. But is the increase in energy use implied actually technically feasible? In other words, are the stocks of fossil fuels in the world large enough to satisfy the demand implied by the BAU scenarios? Or will increasing scarcity drive up the relative prices of fossil fuels sufficiently to choke off demand fast enough to provide a 'laissez faire' answer to the climate-change problem?

There is enough fossil fuel in the ground to meet world consumption demand at reasonable cost until at least 2050.

To date, about 2.7 trillion barrels of oil equivalent (boe) of oil, gas and coal have been used up[43]. At least another 40 trillion boe remain in the ground, of which around 7 trillion boe can reasonably be considered economically recoverable[44]. This is comfortably enough to satisfy the BAU demand for fossil fuels in the period to 2050 (4.7 trillion boe)[45].

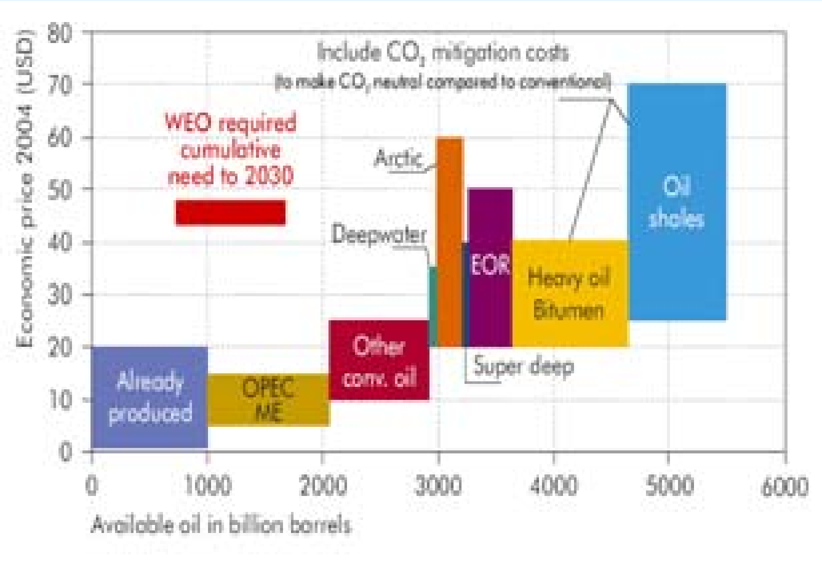
The IEA has looked at where the economically recoverable reserves of oil might come from in the next few decades and the associated extraction costs (see Figure 7.7). Demand for oil in the

---

[43] World Energy Council (2000)
[44] World Energy Council (2000)
[45] IEA (2006)

period to 2050 is expected to be 1.8 trillion boe[46]; this could be extracted at less than $30/barrel. This alone would be enough to raise the concentration of CO_2e in the atmosphere by 50ppm[47].

Figure 7.6 Availability of oil by price[48]



Source: International Energy Agency

There appears to be no good reason, then, to expect large increases in real fossil-fuel prices to be necessary to bring forth supply. Yet big increases in price would be required to hold energy demand and emissions growth in check if no other method were also available. The IEA emissions projections envisage an average annual rate of increase of 1.7% to 2030. If the price elasticity of energy demand were -0.23, an estimate in the middle of the range in the literature[49], the prices of fossil fuels would have to increase by over 7% per year in real terms merely to bring the rate of emissions growth back to zero, implying a more-than-six-fold rise in the real price of energy.

'Carbon capture and storage' technology is important, as it would allow some continued use of fossil fuels and help guard against the risk of fossil-fuel prices falling in response to global climate-change policy, undermining its effectiveness.

There are three major implications for policy. First, it is important to provide incentives to redirect research, development and investment away from the fossil fuels that are currently more difficult to extract (see Grubb (2001)). The initial costs of development provide a hurdle to the exploitation of some of the more carbon-intensive fuels like oil shales and synfuels. This obstacle can be used to help divert R,D&D efforts towards low-carbon energy resources. Second, the low resource costs of much of the remaining stock of fossil fuels have to be taken into account in climate-change policy[50]. Third, as there is a significant element of rent in the current prices of exhaustible fossil-fuel resources, particularly those of oil and natural gas, there is a danger that fossil-fuel prices could fall in response to the strengthening of climate-change policy, undermining its

---

[46] IEA (2006)
[47] This assumes that half of CO_2 emissions are absorbed, as discussed in Chapter 1.
[48] IEA (2005)
[49] See Hunt et al (2003)
[50] In calculating the costs of climate-change mitigation to the world as a whole, fossil-fuel energy should be valued at its marginal resource cost, excluding the scarcity rents, not at its market price. Some estimates of cost savings from introducing alternative energy technologies ignore this point and consequently overestimate the global cost savings.

effectiveness[51]. Extensive carbon capture and storage would maintain the viability of fossil fuels for many uses in a manner compatible with deep cuts in emissions, and thereby help guard against this risk.

---

[51] A downward shift in the demand curve for an exhaustible natural resource is likely to lead to a fall in the current and future price of the resource. In the case of resources for which the marginal extraction costs are very low, this fall could continue until the demand for the fossil fuel is restored. Pindyck (1999) found that the behaviour of oil prices has been broadly consistent with the theory of exhaustible natural resource pricing. See also Chapter 2 references on the pricing of exhaustible natural resources.

References

The World Resources Institute (2005) publication "Navigating the Numbers" provides a very good overview of global GHG emissions, by source and country. The WRI also provides a very user-friendly database in its Climate Analysis Indicators Tool. The International Energy Agency's publications provide an excellent source of information about fossil-fuel emissions and analysis of the medium-term outlook for emissions, energy demand and supply. The US Environmental Protection Agency produces estimates of historical and projected non-CO_2 emissions. Houghton (2005) is a good source of data and information on emissions due to land-use change.

The IPCC's Special Report on Emission Scenarios considers possible longer-term outlooks for emissions and discusses many of the complex issues that arise with any long-term projections. Its scenarios provide the foundation for many of the benchmark 'business as usual' scenarios used in the literature. Some of the difficult challenges posed by the need to make long-term projections have been pursued in the academic literature, for example, in the two papers co-authored by Warwick McKibbin and referenced here and the paper by Schmalensee et al (1998). There have been lively methodological exchanges, including the debates between Castles and Henderson (2003a,b), Nakicenovic et al (2003) and Holtsmark and Alfsen (2005) on how to aggregate incomes across countries. A good example of the Integrated Assessment Model approach to projections can be found in Paltsev et al (2005). Some of the difficulties of untangling the impacts of income and technology on emissions growth are tackled in Huntington (2005), among others.

The World Energy Council (2000) is a good source of information on availability of fossil fuels. The IEA (1995) have also produced an excellent report on this. The extraction costs of fossil fuels are also considered by Rogner (1997). The issues posed by exhaustible fossil fuels in the context of climate change are analysed in papers referenced in Chapter 2.

An, F. and A. Sauer, (2004): 'Comparison of passenger vehicle fuel economy and GHG emission standards around the world', Prepared for the Pew Centre on Global Climate Change, Virginia: Pew Centre.

Asadoorian, M.O., R.S. Eckaus and C.A. Schlosser (2006): 'Modeling climate feedbacks to energy demand: The case of China' MIT Global Change Joint Program Report 135, June, Cambridge, MA: MIT.

Ayres, R. U., Ayres, L. W. and Pokrovsky, V. (2005) 'On the efficiency of US electricity usage since 1900', Energy, 30(7): 1092-1145

Ayres and Warr (2005): 'Accounting for growth: the role of physical work', Structural Change and Economic Dynamics, 16(2): 181-209

Balassa, B. (1964): 'The purchasing power parity doctrine: a reappraisal', Journal of Political Economy, **72**: 584-596

Bosworth, B.P. and S.M. Collins (2003): 'The empirics of growth: an update', Brookings Papers on Economic Activity, No. 2, 2003.

Castles, I. and D. Henderson (2003a): 'The IPCC emissions scenarios: an economic-statistical critique', Energy and Environment,**14**(2-3) May: 159-185

Castles, I. and D. Henderson (2003b): 'Economics, emissions scenarios and the work of the IPCC', Energy and Environment, **14**(4) July: 415-435

Chinese Academy of Social Sciences (2005): 'Understanding China's Energy Policy', Background Paper Prepared for Stern Review on the Economics of Climate Change by the Research Centre for Sustainable Development

EPA (forthcoming) ‘Global anthropogenic non-CO_2 greenhouse-gas emissions: 1990-2020’, US Environmental Protection Agency, Washington DC. Figures quoted from draft December 2005 version.

Grubb, M. (2001): ‘Who’s afraid of atmospheric stabilisation? Making the link between energy resources and climate change’, Energy Policy, **29**: 837-845

Harbaugh, B., A. Levinson and D. Wilson (2002): ‘Reexamining the empirical evidence for an environmental Kuznets Curve,’ Review of Economics and Statistics, **84**(3) August.

Holtsmark, B.J. (2006): ‘Are global per capita CO_2 emissions likely to remain stable?’, Energy & Environment, **17**(2) March.

Holtsmark, B.J. and K.H. Alfsen (2005): ‘PPP correction of the IPCC emissions scenarios – does it matter?’, Climatic Change, **68**(1-2) January: 11-19

Holtz-Eakin, D. and T.M. Selden (1995): ‘Stoking the fires? CO_2 emissions and economic growth’, Journal of Public Economics, **57**, May: 85-101

Houghton, R.A. (2005): 'Tropical deforestation as a source of greenhouse-gas emissions', Tropical Deforestation and Climate Change, (eds.) P. Moutinho and S. Schwartzman, Belém: IPAM - Instituto de Pesquisa Ambiental da Amazônia ; Washington DC - USA : Environmental Defense.
See:
www.environmentaldefense.org/documents/4930_TropicalDeforestation_and_ClimateChange.pdf

Hunt, L.C., G. Judge, and Y. Ninomiya (2003): ‘Modelling underlying energy demand trends’, Chapter 9 in L.C. Hunt (ed), Energy in a competitive market: essays in honour of Colin Robinson, Cheltenham: Edward Elgar.

Huntington, H.G. (2005): ‘US carbon emissions, technological progress and economic growth since 1870’, Int. J. Global Energy Issues, **23**(4): 292-306

International Energy Agency (2005): 'Resources to reserves: oil and gas technologies for the energy markets of the future', Paris: OECD/IEA.

International Energy Agency (2006): 'Energy technology perspectives - scenarios & strategies to 2050', Paris: OECD/IEA.

International Energy Agency (in press): World Energy Outlook 2006, Paris: OECD/IEA.

Intergovernmental Panel on Climate change (2000): 'Emissions Scenarios', Special Report, [N. Nakicenovic and R. Swart (eds.)], Cambridge: Cambridge University Press.

Kaya, Y. (1990): ‘Impact of carbon dioxide emission control on GNP growth: interpretation of proposed scenarios’, paper presented to IPCC Energy and Industry Sub-Group, Response Strategies Working Group.

Lanne, M. and M. Liski (2004): ‘Trends and breaks in per-capita carbon dioxide emissions, 1870-2028’, The Energy Journal, **25**(4): 41-65

McKibbin, W., D. Pearce, and A. Stegman (2004): ‘Long-run projections for climate-change scenarios’, Brookings Discussion Papers in International Economics No 160, April, Washington, DC: The Brookings Institution.

McKibbin, W. and A. Stegman (2005): ‘Convergence and per capita carbon emissions’, Working Paper in International Economics No 4.05, May, Sydney: Lowy Institute fore International Policy.

McKitrick, Ross and Mark C. Strazicich (2005). ‘Stationarity of global per capita carbon dioxide emissions: implications for global warming scenarios’ University of Guelph Department of Economics Discussion Paper 2005-03.

Nakicenovic, N., A. Grübler, S. Gaffin et al. (2003): ‘IPCC SRES revisited: a response’, Energy & Environment, **14**(2-3) May: 187-214

Neumayer, E. (2004): ‘National carbon dioxide emissions: geography matters’, Area, **36**(1): 33-40

Paltsev, S., J.M. Reilly, H.D. Jacoby, et al. (2005): ‘The MIT emissions prediction and policy analysis (EPPA) model: version 4’, MIT Global Change Joint Program Report No. 125, August, Cambridge, MA: MIT.

Pindyck, R.S. (1999): ‘The long-run evolution of energy prices’, The Energy Journal, **20**(2): 1-27

Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat (2005): ‘World population prospects: the 2004 revision highlights’ New York: United Nations.

Pritchett, L. (1997): ‘Divergence, big time’, Journal of Economic Perspectives, **11**(3): 3-17

Quah, D. (1996): 'The invisible hand and the weightless economy', London: London School of Economics Centre for Economic Performance.

Rogner, H.H. (1997): ‘An assessment of world hydrocarbon resources’, Annual Reviews of Energy and the Environment (22): 217-262

Schmalensee, R., T.M. Stoker and R.A. Judson (1998): ‘World carbon dioxide emissions: 1950-2050’, Review of Economics and Statistics, **80**: 15-27

Seldon, T., and D. Song (1994): ‘Environmental quality and development: is there a Kuznets curve for air pollution emissions?’, Journal of Environmental Economics and Management, **27**:7-162

Sue Wing, I. and R.S. Eckaus (2004): ‘Explaining long-run changes in the energy intensity of the US economy’, MIT Global Change Joint Program, Report No 116, September, Cambridge, MA: MIT.

World Energy Council (2000): World Energy Assessment: Energy and the challenge of sustainability, New York: United Nations Development Programme.

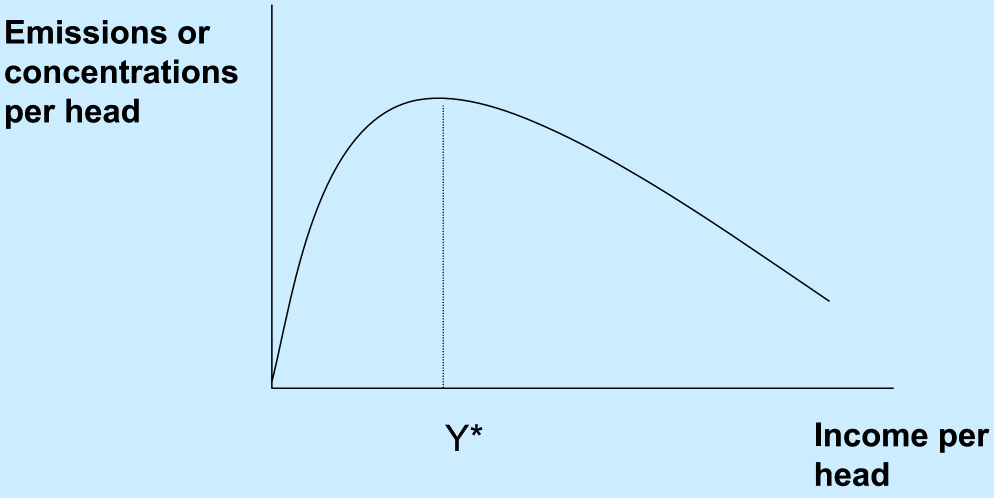
World Resources Institute (2005): ‘Navigating the numbers’, World Resources Institute, Washington DC.

World Resources Institute (2006): Climate Analysis Indicators Tool (CAIT) on-line database version 3.0., Washington, DC: World Resources Institute, available at: http://cait.wri.org

Annex 7A Climate Change and the Environmental Kuznets Curve

Some evidence indicates that, for local pollutants like oxides of nitrogen, sulphur dioxide and heavy metals, there is an inverted-U shaped relationship between income per head and emissions per head: the so-called ‘environmental Kuznets curve’, illustrated in Figure 7.7[52]. The usual rationale for such a curve is that the demand for environmental improvements is income elastic, although explanations based on structural changes in the economy have also been put forward. So the question arises, is there such a relationship for CO_2? If so, economic development would ultimately lead to falls in global emissions (although that would be highly unlikely before GHG concentrations had risen to destructive levels).

Figure 7A.1 ’A hypothetical environmental Kuznets curve’



In the case of greenhouse gases, this argument is not very convincing. As societies become richer, they may want to improve their own environment, but they can do little about climate change by reducing their own CO_2 emissions alone. With CO_2, the global nature of the externality means that people in any particular high-income country cannot by themselves significantly affect global emissions and hence their own climate. This contrasts with the situation for the local pollutants for which environmental Kuznets curves have been estimated. It is easier than with greenhouse gases for the people affected to set up abatement incentives and appropriate political and regulatory mechanisms. Second, CO_2 had not been identified as a pollutant until around 20 years ago, so an explanation of past data based on the demand for environmental improvements does not convince.

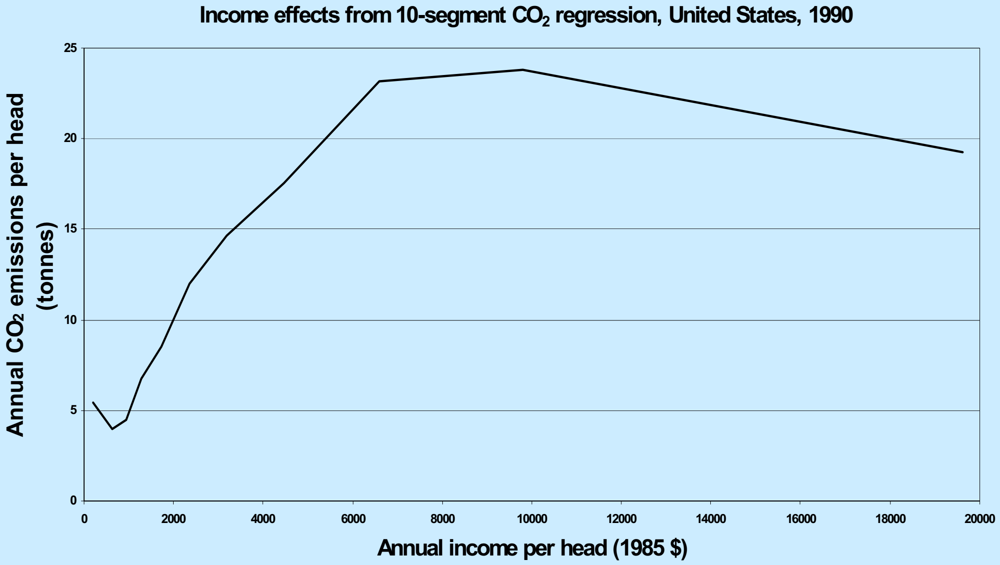
Nevertheless, patterns like the one in Figure 7.4 suggest that further empirical investigation of the relationship between income and emissions is warranted. The relationship could reflect changes in the structure of production as countries become better off, as well as or instead of changes in the pattern of demand for environmental improvements. Several empirical studies[53] have found that a relationship looking something like the first half of an environmental Kuznets curve exists for CO_2 (after allowing for some other explanatory factors in some, but not all, cases). Figure 7.8 illustrates this, using Schmalensee et al’s estimates for the United States.

---

[52] See Seldon and Song (1994) and Harbaugh et al (2002)

[53] See, inter alia, Neumayer, op. cit., Holtz-Eakin and Selden (1995) and Schmalensee et al, op. cit.

Figure 7A. 2 'Income effects from 10-segment CO_2 regression, USA, 1990'



Source: Schmalensee et al (1998)

Even if this finding *were* robust, however, it does not imply that the global relationship between GDP per head and CO_2 emissions per head is likely to disappear soon. The estimated turning points at which CO_2 emissions start to fall are at very high incomes (for example, between $55.000 and $90,000 in Neumayer's cross-country study, in which the maximum income level observed in the data was $41,354). Poor and middle-income countries will have to grow for a long time before they get anywhere near these levels. Schmalensee et al found that, using their estimates – *with* an implied inverted-U shape – as the basis for a projection of future emissions, emissions growth was likely to be positive up to their forecast horizon of 2050; indeed, they forecast more rapid growth than in nearly all the 1992 IPCC scenarios, using the same assumptions as the IPCC for future population and income growth.

In any case, it is not clear that the link between emissions and income does disappear at high incomes. First, the apparent turning points in some of the studies may simply be statistical artefacts, reflecting the particular functional forms for the relationship assumed by the researchers[54]. Second, the apparent weakening of the link may result from ignoring the implications of past changes in energy technology; after controlling for the adoption of new technologies that, incidentally, were less carbon-intensive, the link may reappear, as argued by Huntington (2005).

---

[54] This is not the case with the 'piecewise segments' approach of Schmalensee et al.

8 The Challenge of Stabilisation

Key Messages

The world is already irrevocably committed to further climate changes, which will lead to adverse impacts in many areas. Global temperatures, and therefore the severity of impacts, will continue to rise unless the stock of greenhouse gases is stabilised. Urgent action is now required to prevent temperatures rising to even higher levels, lowering the risks of impacts that could otherwise seriously threaten lives and livelihoods worldwide.

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. In the long term, global emissions will need to be reduced to less than 5 $GtCO_2e$, over 80% below current annual emissions, to maintain stabilisation. The longer emissions remain above the level of natural absorption, the higher the final stabilisation level will be.

Stabilisation cannot be achieved without global action to reduce emissions. Early action to stabilise this stock at a relatively low level will avoid the risk and cost of bigger cuts later. The longer action is delayed, the harder it will become.

Stabilising at or below 550 ppm CO_2e (around 440 - 500 ppm CO_2 only) 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. 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 three to four times larger than today – so emissions per unit of GDP would need to be just one quarter of current levels by 2050.

Delaying the peak in global emissions from 2020 to 2030 would almost double the rate of reduction needed to stabilise at 550 ppm CO_2e. A further ten-year delay could make stabilisation at 550 ppm CO_2e impractical, unless early actions were taken to dramatically slow the growth in emissions prior to the peak.

To stabilise at 450 ppm 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. This is likely to be unachievable with current and foreseeable technologies.

If carbon absorption were to weaken, future emissions would need to be cut even more rapidly to hit any given stabilisation target for atmospheric concentration.

Overshooting paths involve greater risks to the climate than if the stabilisation level were approached from below, as the world would experience at least a century of temperatures, and therefore impacts, close to those expected for the peak level of emissions. Some of these impacts might be irreversible. In addition, overshooting paths require that emissions be reduced to extremely low levels, below the level of natural absorption, which may not be feasible.

Energy systems are subject to very significant inertia. It is important to avoid getting 'locked into' long-lived high carbon technologies, and to invest early in low carbon alternatives.

8.1 Introduction

The stock of greenhouse gases in the atmosphere is already at 430 ppm CO_2e and currently rising at roughly 2.5 ppm every year. The previous chapter presented clear evidence that greenhouse gas emissions will continue to increase over the coming decades, forcing the stock of greenhouse gases upwards at an accelerating pace. Parts I and II demonstrated that, if emissions continue unabated, the world is likely to experience a radical transformation of its climate, with profound implications for our way of life.

Global mean temperatures will continue to rise unless the stock of greenhouse gases in the atmosphere is stabilised. This chapter considers the pace, scale and composition of emissions paths associated with stabilisation. This is a crucial foundation for examining the costs of stabilisation; which are discussed in the following two chapters.

The first section of this chapter looks at what different stabilisation levels mean for global temperature rises and presents the science of how to stabilise greenhouse gas levels. The following two sections go on to consider stabilisation of carbon dioxide and other gases in detail. Sections 8.4 and 8.5 uses preliminary results from a simple model to examine the emissions cuts required to stabilise the stock of greenhouse gases in the range 450 – 550 ppm CO_2e, and the implications of delaying emissions cuts. The final section gives a more general discussion of the scale of the challenge of achieving stabilisation.

The focus on the range 450 – 550 ppm CO_2e is based on analyses presented in chapter 13, which conclude that stabilisation at levels below 450 ppm CO_2e would require immediate, substantial and rapid cuts in emissions that are likely to be extremely costly, whereas stabilisation above 550 ppm CO_2e would imply climatic risks that are very large and likely to be generally viewed as unacceptable.

8.2 Stabilising the stock of greenhouse gases

The higher the stabilisation level, the higher the ultimate average global temperature increase will be.

The relationship between stabilisation levels and temperature rise is not known precisely (chapter 1). Box 8.1 summarises recent studies that have tried to establish probability distributions for the ultimate temperature increase associated with given greenhouse gas levels. It shows the warming that is expected when the climate comes into equilibrium with the new level of greenhouse gases; it can be understood as the warming committed to in the long run. In most cases, this would be higher than the temperature change expected in 2100.

Box 8.1 shows, for example, that stabilisation at 450 ppm CO_2e would lead to an around 5 – 20% chance of global mean temperatures ultimately exceeding 3°C above pre-industrial (from probabilities based on the IPCC Third Assessment Report (TAR) and recent Hadley Centre work). An increase of more than 3°C would entail very damaging physical, social and economic impacts, and heightened risks of catastrophic changes (chapter 3). For stabilisation at 550 ppm CO_2e, the chance of exceeding 3°C rises to 30 – 70%. At 650 ppm CO_2e, the chance rises further to 60 – 95%.

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.

To stabilise greenhouse gas concentrations, emissions must be reduced to a level where they are equal to the rate of absorption/removal by natural processes. This level is different for different greenhouse gases. The longer global emissions remain above this level, the higher the stabilisation level will be. It is the *cumulative* emissions of greenhouse gases, less their cumulative removal from the atmosphere, for example by chemical processes or through absorption by the Earth's natural systems, that defines their concentration at stabilisation. The following section examines the stabilisation of carbon dioxide concentrations. The stabilisation of other gases in discussed separately in section 8.4.

Box 8.1 Likelihood of exceeding a temperature increase at equilibrium

This table provides an indicative range of likelihoods of exceeding a certain temperature change (at equilibrium) for a given stabilisation level (measured in CO_2 equivalent). For example, for a stock of greenhouse gases stabilised at 550 ppm CO_2e, recent studies suggest a 63 - 99 % chance of exceeding a warming of 2°C relative to the pre-industrial.

The data shown is based on the analyses presented in Meinshausen (2006), which brings together climate sensitivity distributions from eleven recent studies (chapter 1). Here, the ‘maximum’ and ‘minimum’ columns give the maximum and minimum chance of exceeding a level of temperature increase across all eleven recent studies. The ‘Hadley Centre’ and ‘IPCC TAR 2001’ columns are based on Murphy *et al.* (2004) and Wigley and Raper (2001), respectively. These results lie close to the centre of the range of studies (Box 1.2). The ‘IPCC TAR 2001’ results reflect climate sensitivities of the seven coupled ocean-atmosphere climate models used in the IPCC TAR. The individual values should be treated as approximate.

The red shading indicates a 60 per cent chance of exceeding the temperature level; the amber shading a 40 per cent chance; yellow shading a 10 per cent chance; and the green shading a less than a 10 per cent chance.

Stabilisation Level (CO_2e)	Maximum	Hadley Centre Ensemble	IPCC TAR 2001 Ensemble	Minimum
Probability of exceeding 2°C (relative to pre-industrial levels)				
400	57%	33%	13%	8%
450	78%	78%	38%	26%
500	96%	96%	61%	48%
550	99%	99%	77%	63%
650	100%	100%	92%	82%
750	100%	100%	97%	90%
Probability of exceeding 3°C (relative to pre-industrial levels)				
400	34%	3%	1%	1%
450	50%	18%	6%	4%
500	61%	44%	18%	11%
550	69%	69%	32%	21%
650	94%	94%	57%	44%
750	99%	99%	74%	60%
Probability of exceeding 4°C (relative to pre-industrial levels)				
400	17%	1%	0%	0%
450	34%	3%	1%	0%
500	45%	11%	4%	2%
550	53%	24%	9%	6%
650	66%	58%	25%	16%
750	82%	82%	41%	29%
Probability of exceeding 5°C (relative to pre-industrial levels)				
400	3%	0%	0%	0%
450	21%	1%	0%	0%
500	32%	3%	1%	0%
550	41%	7%	2%	1%
650	53%	24%	9%	5%
750	62%	47%	19%	11%

8.3 Stabilising carbon dioxide concentrations

Carbon dioxide concentrations have risen by over one third, from 280 ppm pre-industrial to 380 ppm in 2005. The current concentration of carbon dioxide in the atmosphere accounts for around 70% of the total warming effect (the ‘radiative forcing’) of all Kyoto greenhouse gases[1].

---

[1] The conversion to radiative forcing is given in IPCC (2001).

Over the past two centuries, around 2000 $GtCO_2$ have been released into the atmosphere through human activities (mainly from burning fossil fuels and land-use changes)[2]. The Earth's soils, vegetation and oceans have absorbed an estimated 60% of these emissions, leaving 800 $GtCO_2$ to accumulate in the atmosphere. This corresponds to an increase in the concentration of carbon dioxide in the atmosphere of 100 parts per million (ppm), thus an *accumulation* of around 8 $GtCO_2$ corresponds to a 1 ppm rise in concentration.

Accordingly, a carbon dioxide concentration of 450 ppm, around 70 ppm more than today, would correspond to a further *accumulation* of around 550 $GtCO_2$ in the atmosphere. However, the cumulative *emissions* that would be expected to lead to this concentration level would be larger, as natural processes should continue to remove a substantial portion of future carbon dioxide emissions from the atmosphere.

Note that, a carbon dioxide concentration of 450 ppm would be equivalent to a total stock of greenhouse gases of at least 500 ppm CO_2e (depending on emissions of non-CO_2 gases).

Today, for every 15 - 20 $GtCO_2$ *emitted*, the concentration of carbon dioxide rises by a further 1 ppm, with natural processes removing the equivalent of roughly half of all emissions. But, the future strength of natural carbon absorption is uncertain. It will depend on a number of factors, including:

- The sensitivity of carbon absorbing systems, such as forests, to future climate changes.
- Direct human influences, such as clearing forests for agriculture.
- The sensitivity of natural processes to the rate of increase and level of carbon dioxide in the atmosphere. For example, higher levels of carbon dioxide can stimulate a higher rate of absorption by vegetation (the carbon fertilisation effect – chapter 3).

Assuming that climate does not affect carbon absorption, a recent study projects that stabilising carbon dioxide concentrations at 450 ppm would allow cumulative *emissions* of close to 2100 $GtCO_2$ between 2000 and 2100 (Figure 8.1)[3] (equivalent to roughly 60 years of emissions at today's rate). This means that approximately 75% of emissions would have been absorbed. Stabilising at 550 ppm CO_2 would allow roughly 3700 $GtCO_2$.

Land use management, such as afforestation and reforestation, can be used to enhance natural absorption, slowing the accumulation of greenhouse gases in the atmosphere and increasing the permissible cumulative level of human emissions at stabilisation. However, this can only be one part of a mitigation strategy; substantial emissions reduction will be required from many sectors to stabilise carbon dioxide concentrations (discussed further in chapter 9).

There is now strong evidence that natural carbon absorption will weaken as the world warms (chapter 1). This would make stabilisation more difficult to achieve.

A recent Hadley Centre study shows that if feedbacks between the climate and carbon cycle are included in a climate model, the resulting weakening of natural carbon absorption means that the cumulative emissions at stabilisation are dramatically reduced. Figure 8.1 shows that to stabilise carbon dioxide concentrations at 450 – 750 ppm, cumulative emissions must be 20 – 30% lower than previously estimated. For example, the cumulative emissions allowable to stabilise at 450 ppm CO_2 are reduced by 500 $GtCO_2$, or around fifteen years of global emissions at the current rate. This means that emissions would need to peak at a lower level, or be cut more rapidly, to achieve a desired stabilisation goal. The effects are particularly severe at higher stabilisation levels.

---

[2] Extrapolating to 2005 from Prentice *et al.* (2001), which gives 1800 $GtCO_2$ total emissions in 2000 and a 90 ppm increase in atmospheric carbon dioxide concentration. The extrapolation assumes 2000 emissions to 2005.

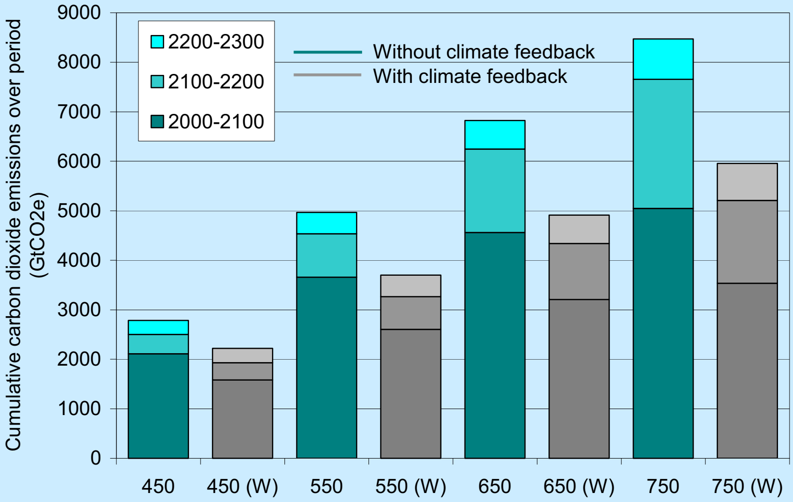
[3] Based on Jones *et al.* 2006, assuming no climate-carbon feedback.

The uncertainties over future carbon absorption make a powerful argument for taking an approach that allows for the possibility that levels of effort may have to increase later to reach a given goal.

Not taking into account the uncertainty in future carbon absorption, including the risk of weakening carbon absorption, could lead the world to overshoot a stabilisation goal. As the scientific understanding of this effect strengthens, adjustments will need to be made to the estimates of trajectories consistent with different levels of stabilisation.

Figure 8.1 Cumulative emissions of carbon dioxide at stabilisation

This figure gives illustrative results from one study that shows the level of cumulative emissions between 2000 and 2300 for a range of stabilisation levels (carbon dioxide only). For the green bars, natural carbon absorption is not affected by the climate. The grey bars include the feedbacks between the climate and the carbon cycle (stabilisation levels labelled as (W)). Comparison of these sets of bars shows that if natural carbon absorption weakens (as predicted by the model used) then the level of cumulative emissions associated with a stabilisation goal reduces. The intervals on the bars show emissions to 2100 and 2200.



Source: based on Jones et al. (2006)

To stabilise concentrations of carbon dioxide in the long run, emissions will need to be cut by more than 80% from 2000 levels.

To achieve stabilisation, annual carbon dioxide emissions must be brought down to a level where they equal the rate of natural absorption. After stabilisation, the level of natural absorption will gradually fall as the vegetation sink is exhausted. This means that to maintain stabilisation, emissions would need to fall to the level of ocean uptake alone over a few centuries. This level is not well quantified, but recent work suggests that emissions may need to fall to roughly 5 $GtCO_2e$ per year (more than 80% below current levels) by the second half of the next century[4]. On a timescale of a few hundred years, this could be considered a 'sustainable' rate of emissions[5]. However, in the long term, the rate of ocean uptake will also weaken, meaning that emissions may eventually need to fall below 1$GtCO_2e$ per year to maintain stabilisation.

Reducing annual emissions below the rate of natural absorption would lead to a fall in concentrations. However, such a recovery would be a very slow process; even if very low

---

[4] The two carbon cycle models used in the IPCC Third Assessment Report project emissions falling to around 3 – 9$GtCO_2$ per year by around 2150 - 2300 (longer for higher stabilisation levels) (Prentice et al. (2001), Figure 3.13).

[5] See Jacobs (1991) for discussion of operationalising the concept of sustainability for complex issues.

emissions were achieved, concentrations would only fall by a few parts per million (ppm) per year[6]. This rate would be further reduced if carbon absorption were to weaken as projected.

8.4 Stabilising concentrations of non-CO_2 gases

Non-CO_2 gases account for one quarter of the total 'global warming potential' of emissions and therefore, must play an important role in future mitigation strategies.

Global warming potentials (GWP) provide a way to compare greenhouse gases, which takes into account both the warming affect and lifetime[7] of different gases. The 100-year GWP is most commonly used; this is equal to *the ratio of the warming affect (radiative forcing) from 1kg of a greenhouse gas to 1kg of carbon dioxide over 100 years.* Over a hundred year time horizon, methane has a GWP twenty-three times that of carbon dioxide, nitrous oxide nearly 300 times and some fluorinated gases are thousands of times greater (Table 8.1).

This leads to a measure, also known as CO_2 equivalent (CO_2e), which weights emissions by their global warming potential. This measure is used as an exchange metric to compare the long-term impact of different emissions. Table 8.1 shows the portion of 2000 emissions made up by the different Kyoto greenhouse gases in terms of CO_2e. Note that, in this Review, CO_2 equivalent emissions are defined differently to CO_2 equivalent concentrations, which consider the *instantaneous* warming effect of the gas in the atmosphere. For example, non-CO_2 Kyoto gases make up around one quarter of total emissions in terms of their long term warming potential in 2000 (Table 3.1). However, they account for around 30% of the total warming effect (the radiative forcing) of non-CO_2 gases in the atmosphere today.

Table 8.1 Characteristics of Kyoto Greenhouse Gases

Despite the higher GWP of other greenhouse gases over a 100-year time horizon, carbon dioxide constitutes around three-quarters of the total GWP of emissions. This is because the vast majority of emissions, by weight, are carbon dioxide. HFCs and PFCs include many individual gases; the data shown are approximate ranges across these gases.

	Lifetime in the atmosphere (years)	100-year Global Warming Potential (GWP)	Percentage of 2000 emissions in CO_2e
Carbon dioxide	5-200	1	77%
Methane	10	23	14%
Nitrous Oxide	115	296	8%
Hydrofluorocarbons (HFCs)	1 – 250	10 – 12,000	0.5%
Perfluorocarbons (PFCs)	>2500	>5,500	0.2%
Sulphur Hexafluoride (SF_6)	3,200	22,200	1%

Source: Ramaswamy et al. (2001)[8] and emissions data from the WRI CAIT database[9].

As methane is removed from the atmosphere much more rapidly than carbon dioxide, its short term effect is even greater than is suggested by its 100-year GWP. However, over-reliance on abatement of gases with strong warming effects but short lifetimes could lock in long term impacts from the build up of carbon dioxide. Some gases, like HFCs, PFCs and SF_6, have both a stronger warming effect and longer lifetime than CO_2, therefore abating their emissions is very important in the long run.

The stock of different greenhouse gases at stabilisation will depend on the exact stabilisation strategy adopted. In the examples used in this chapter, stabilising the stock of all Kyoto greenhouse gases at 450 – 550 ppm CO_2e would mean stabilising carbon dioxide

---

[6] For example, O'Neill and Oppenheimer (2005).

[7] The lifetime of a gas is a measure of the average length of time that a molecule of gas remains in the atmosphere before it is removed by chemical or physical processes.

[8] These estimates are from the Third Assessment Report of the IPCC (Ramaswamy et al. (2001)). The UNFCCC uses slightly different GWPs based on the Second Assessment Report (http://ghg.unfccc.int/gwp.html).

[9] The World Resources Institute (WRI) Climate Analysis Indicators Tool (CAIT): http://cait.wri.org/

concentrations at around 400 – 490 ppm. More intensive carbon dioxide mitigation, relative to other gases, might lead to a lower fraction of carbon dioxide at stabilisation, and vice versa. Two recent cost optimising mitigation studies find that, at stabilisation, non-CO_2 Kyoto gases contribute around 10 – 20% of the total warming effect expressed in CO_2e[10]. Therefore, a stabilisation range of 450 – 550 ppm CO_2e, could mean carbon dioxide concentrations of 360 – 500 ppm. The cost implications of multi-gas strategies are discussed further in chapter 10.

It is the total warming effect (or radiative forcing), expressed as the stock in terms of CO_2 equivalent, which is critical in determining the impacts of climate change. For this reason, this Review discusses stabilisation in terms of the total stock of greenhouse gases.

8.5 Pathways to stabilisation

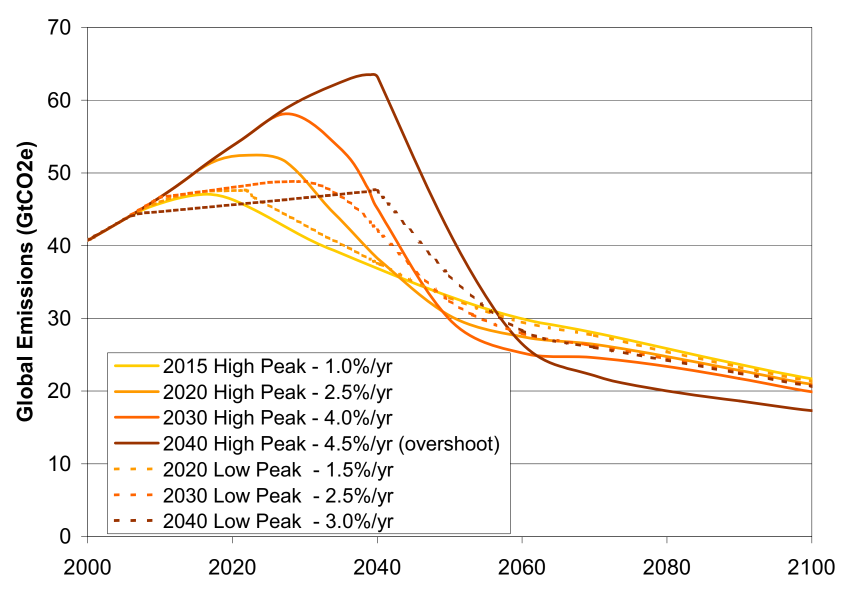
As discussed above, stabilisation at any level ultimately requires a cut in emissions down to less than 20% of current levels. The question then becomes one of how quickly stabilisation can be achieved. If action is slow and emissions stay high for a long time, the ultimate level of stabilisation will be higher than if early and ambitious action is taken.

The rate of emissions cuts required to meet a stabilisation goal is very sensitive to both the timing of the peak in global emissions, and its height. Delaying action now means more drastic emissions reductions over the coming decades.

There are a number of possible emissions trajectories that can achieve any given stabilisation goal. For example, emissions can peak early and decline gradually, or peak later and decline more rapidly. This is demonstrated in Figure 8.2, which shows illustrative pathways to stabilisation at 550 ppm CO_2e.

Figure 8.2 Illustrative emissions paths to stabilise at 550 ppm CO_2e.

The figure below shows six illustrative paths to stabilisation at 550 ppm CO_2e. The rates of emissions cuts are given in the legend and are the *maximum* 10-year average rate (see Table 8.2). 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: Generated with the SiMCaP EQW model (Meinshausen et al. 2006)

---

[10] For example, Meinshausen (2006) and US CCSP (2006)

Table 8.2 Illustrative Emissions Paths to Stabilisation

The table below explores the sensitivity of rates of emissions reductions to the stabilisation level and timing and size of the peak in global emissions. These results were generated using the SiMCaP EQW model, as used in Meinshausen *et al.* (2006), and should be treated as indicative of the scale of emissions reductions required.

The table covers three stabilisation levels and a range of peak emissions dates from 2010 to 2040. The centre column shows the implied rate of global emissions reductions. The value shown is the *maximum* 10-year average rate. As shown in Figure 8.2, the rate of emissions reductions accelerates after the peak and then slows in the second half of the century. The *maximum* 10-year average rate is typically required in the 5 – 10 years following the peak in global emissions. The range of rates shown in each cell is important: the lower bound illustrates the rate for a low peak in global emissions (that is, action is taken to slow the rate of emissions growth prior to the peak) – in this example, these trajectories peak at not more than 10% above current levels; the upper bound assumes no substantial action prior to the peak (note that emissions in this case are still below IEA projections – see Figure 8.4).

The paths use the assumption of a maximum 10%/yr reduction rate. A symbol "-" indicates that stabilisation is not possible given this assumption. Grey italic figures indicate overshooting. The overshoots are numbered in brackets '[ ]' and details given below the table.

Stabilisation Level (CO$_2$e)	Date of peak global emissions	Global emissions reduction rate (% per year)	Percentage reduction in emissions below 2005* values	
			2050	2100
450 ppm	2010	7.0	70	75
	2020	-	-	-
500 ppm (falling to 450 ppm in 2150)	2010	3.0	50	75
	2020	4.0 - 6.0	60 - 70	75
	2030	*5.0[1] – 5.5 [2]*	*50 - 60*	*75 – 80*
	2040	-	-	-
550 ppm	2015	1.0	25	50
	2020	1.5 – 2.5	25 – 30	50 – 55
	2030	2.5 – 4.0	25 – 30	50 – 55
	2040	3.0 – *4.5 [3]*	*5* – 15	50 – *60*

Notes: overshoots: [1] to 520 ppm, [2] to 550 ppm, [3] to 600 ppm. 2005 emissions taken as 45 GtCO$_2$e/yr.
Source: Generated with the SiMCaP EQW model and averaged over multiple scenarios (Meinshausen et al. 2006)

The height of the peak is also crucial. If early action is taken to substantially slow the growth in emissions prior to the peak, this will significantly reduce the required rate of reductions following the peak. For example, in Figure 8.2, if action is taken to ensure that emissions peak at only 7% higher than current levels, rather than 15% higher in 2020 to achieve stabilisation at 550 ppm CO$_2$e, the rate of reductions required after 2020 is almost halved.

If the required rate of emissions cuts is not achieved, the stock of greenhouse gases will overshoot the target level. Depending on the size of the overshoot, it could take at least a century to reduce concentrations back to a target level (discussed later in Box 8.2).

Table 8.2 gives examples of implied reduction rates for stabilisation levels between 550 ppm and 450 ppm CO$_2$e. A higher stabilisation level would require weaker cuts. For example, to stabilise at 650 ppm CO$_2$e, emissions could be around 20% above current levels by 2050, and 35% below current levels by 2100. As described in section 8.2, this higher stabilisation level would mean a much greater chance of exceeding high levels of warming and therefore, a higher risk of more adverse and unacceptable outcomes. The paths shown in Table 8.2 are based on one model and should be treated as indicative. Despite this, they provide a crucial illustration of the scale of the challenge. Further research is required to explore the uncertainties and inform more detailed strategies on future emissions paths.

To stabilise at 550 ppm CO_2e, global emissions would need to peak in the next 10 – 20 years and then fall by around 1 – 3% per year. Depending on the exact trajectory taken, global emissions would need to be around 25% lower than current levels by 2050, or around 30-35 $GtCO_2$.

If global emissions peak by 2015, then a reduction rate of 1% per year should be sufficient to achieve stabilisation at 550 ppm CO_2e (Table 8.2). This would mean immediate, substantial and global action to prepare for this transition. Given the current trajectory of emissions and inertia in the global economy, such an early peak in emissions looks very difficult. But the longer the peak is delayed, the faster emissions will have to fall afterwards. For a delay of 15 years in the peak, the rate of reduction must more than double, from 1% to between 2.5% and 4.0% per year, where the lower value assumes a lower peak in emissions (see Figure 8.2). Given that it is likely to be difficult to reduce emissions faster than around 3% per year (discussed in the following section), this emphasises the importance of urgent action now to slow the growth of global emissions, and therefore lower the peak.

A further 10-year delay would mean a reduction rate of at least 3% per year, assuming that action is taken to substantially slow emissions growth; if emissions growth is not slowed significantly, stabilisation at 550 ppm CO_2e may become unattainable without overshooting.

Stabilising at 450 ppm CO_2e or below, without overshooting, is likely to be very costly because it would require around 7% per year emission reductions.

Table 8.2 illustrates that even if emissions peaked in 2010, they would have to fall by around 7% per year to stabilise at 450 ppm CO_2e without overshooting[11]. This would take annual emissions to 70% below current levels, or around 13 $GtCO_2$ by 2050. This is an extremely rapid rate, which is likely to be very costly. For example, 13$GtCO_2$ is roughly equivalent to the annual emissions from agriculture and transport alone today.

Achieving this could mean, for example, a rapid and complete decarbonisation of non-transport energy emissions, halting deforestation and substantial intensification of sequestration activities. The achievability of stabilisation levels is discussed in more detail in the following sections and in chapter 9.

Allowing the stock to peak at 500 ppm CO_2e before stabilising at 450 ppm (an 'overshooting' path to stabilisation, Box 8.2) would decrease the required annual reduction rate from around 7% to 3%, if emissions were to peak in 2010. However, overshooting paths, in general, involve greater risks.

An overshooting path to any stabilisation level would lead to greater impacts, as the world would experience a century or more of temperatures close to those expected for the peak level (discussed later in Figure 8.3). Given the large number of unknowns in the climate system, for example, threshold points and irreversible changes, overshooting is potentially high risk. In addition, if natural carbon absorption were to weaken as projected, it might be impossible to reduce concentrations on timescales less than a few centuries.

Given the extreme rates of emissions cuts required to stabilise at 450 ppm CO_2e, in this case overshooting may be unavoidable. The risks involved in overshooting can be reduced through minimising the size of the overshoot by taking substantial, early action to cut emissions.

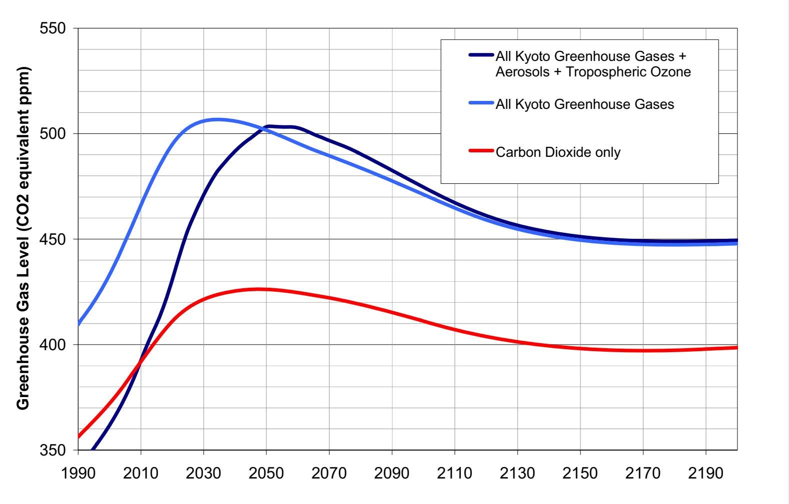
---

[11] An atmospheric greenhouse gas level of 450 ppm is less than 10 years away, given that concentrations are rising at 2.5 ppm per year (chapter 3). However, in the scenarios outlined in Table 8.1, aerosol cooling temporarily offsets some of the increase in greenhouse gases, giving more time to stabilise. This effect is illustrated in Box 8.2.

Box 8.2 Overshooting paths to stabilisation

The figure below illustrates an overshooting path to stabilisation at 450 ppm CO_2e (or 400 ppm CO_2 only) – this is characterised by greenhouse gas levels peaking above the stabilisation goal and then reducing over a period of at least a century.

The light blue line shows the level of all Kyoto greenhouse gases in CO_2e (the Review definition) and the red line shows the level of carbon dioxide alone. The dark blue line shows a third measure of greenhouse gas level that includes aerosols and tropospheric ozone. This is the measure used in the Meinshausen *et al.* trajectories shown in this chapter. The gap between the two blue lines in the early period is mainly due to the cooling effect of aerosols. Critically, by 2050 the lines converge as it is assumed that aerosol emissions diminish.



Source: Generated with the SiMCaP EQW model (Meinshausen et al. 2006)

8.6 Timing of Emissions Reductions

Pathways involving a late peak in emissions may effectively rule out lower stabilisation trajectories and give less margin for error, making the world more vulnerable to unforeseen changes in the Earth's system.

Early abatement paths offer the option to switch to a lower emissions path if at a later date the world decides this is desirable. This might occur for example, if natural carbon absorption weakened considerably (section 8.3) or the damages associated with a stabilisation goal were found to be greater than originally thought. Similarly, aiming for a lower stabilisation trajectory may be a sensible hedging strategy, as it is easier to adjust upwards to a higher trajectory than downwards to a lower one.

Late abatement trajectories carry higher risks in terms of climate impacts; overshooting stabilisation paths incur particularly high risks.

The impacts of climate change are not only dependent on the final stabilisation level, but also the path to stabilisation. Figure 8.3 shows that if emissions are accumulated more rapidly, this will lead to a more rapid rise in global temperatures. Figure 8.3 demonstrates the point made in the last section, that overshooting paths lead to particularly high risks, as temperatures rise more rapidly and to a higher level than if the target were approached from below.

Early abatement may imply lower long-term costs through limiting the accumulation of carbon-intensive capital stock in the short term.

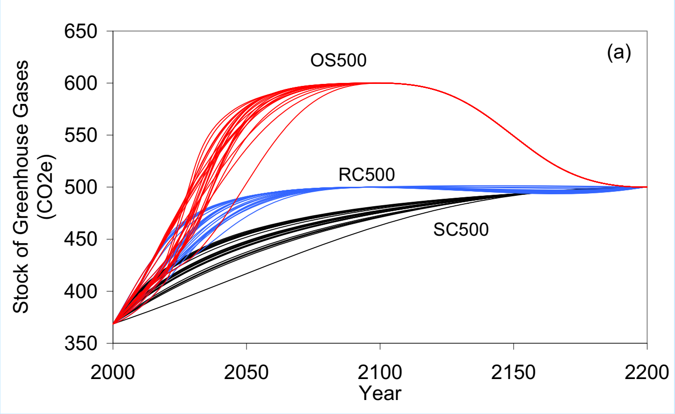
Delaying action risks getting 'locked into' long-lived high carbon technologies. It is crucial to invest early in low carbon technologies. Technology policies are discussed in chapter 15.

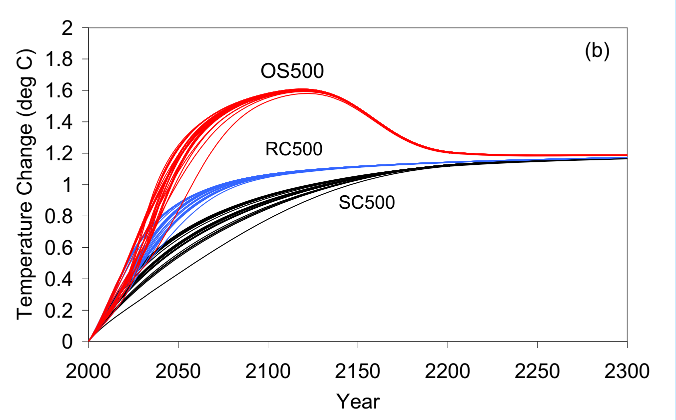
Figure 8.3 Implications of Early versus Late Abatement

The figure below is an illustrative example of the rate of change in (a) the stock of greenhouse gases and (b) global mean temperatures, for a set of slow (SC, black), rapid (RC, blue) and overshooting (OS, red) paths to stabilisation at 500 ppm CO_2e.

On the slow paths, emissions cuts begin early and progress at a gradual pace, leading to a gradual increase in greenhouse gas concentrations and therefore, temperatures. On the rapid paths, reductions are delayed, requiring stronger emissions cuts later on. This leads to a more rapid increase in temperature as emissions are accumulated more rapidly early on. The overshooting path has even later action, causing concentrations and temperatures to rise rapidly, as well as peaking at a higher level before falling to the stabilisation level.

The higher rate of temperature rise associated with the delayed action paths (RC and OS) would increase the risk of more severe impacts. Temperatures associated with the overshooting path rise at more than twice the rate of the slow path (more than 0.2°C/decade) for around 80 years and rise to a level around 0.5°C higher. Many systems are sensitive to the rate of temperature increase, most notably ecosystems, which may be unable to adapt to such high rates of temperature change.





Source: redrawn from O'Neill and Oppenheimer (2004). The temperature calculations assume a climate sensitivity of 2.5°C (see chapter 1), giving an eventual warming of 2.1°C relative to pre-industrial.

Paths requiring very rapid emissions cuts are unlikely to be economically viable.

To meet any given stabilisation level, a late peak in emissions implies relatively rapid cuts in annual emissions over a sustained period thereafter. However, there is likely to be a maximum practical rate at which global emissions can be reduced. At the national level, there are examples of sustained emissions cuts of up to 1% per year associated with structural change in energy systems (Box 8.3). One is the UK 'dash for gas'; a second is France, which, by switching to a nuclear power-based economy, saw energy-related emissions fall by almost 1% per year between 1977 and 2003, whilst maintaining strong economic growth.

However, cuts in emissions greater than this have historically been associated only with economic recession or upheaval, for example, the emissions reduction of 5.2% per year for a decade associated with the economic transition and strong reduction in output in the former Soviet Union. These magnitudes of cuts suggest it is likely to be very challenging to reduce emissions by more than a few percent per year while maintaining strong economic growth.

Box 8.3 Historical reductions in national emissions

Experience suggests it is difficult to secure emission cuts faster than about 1% per year except in instances of recession. Even when countries have adopted significant emission saving measures, national emissions often rose over the same period.

- **Nuclear power in France**: In the late 1970s, France invested heavily in nuclear power. Nuclear generation capacity increased 40-fold between 1977 and 2003 and emissions from the electricity and heat sector fell by 6% per year, against a background 125% increase in electricity demand. The reduction in total fossil fuel related emissions over the same period was less significant (0.6% per year) because of growth in other sectors.

- **Brazil's biofuels**: Brazil scaled up the share of biofuels in total road transport fuel from 1% to 25% from 1975 to 2002. This had the effect of slowing, but not reversing, the growth of road transport emissions, which rose by 2.8% per year with biofuels, but would otherwise have risen at around 3.6% per year. Total fossil fuel related emissions from Brazil rose by 3.1% pa over the same period.

- **Forest restoration in China**: China embarked on a series of measures to reduce deforestation and increase reforestation from the 1980s, with the aim of restoring forests and the environmental benefits they entail. Between 1990 and 2000 forested land increased by 18m hectares from 16% to 18% of total land area[12]. Despite cuts in land use emissions of 29% per year between 1990 and 2000[13], total GHG emissions rose by 2.2% over the same period.

- **UK 'Dash for Gas'**: An increase in coal prices in the 1990s relative to gas encouraged a switch away from coal towards gas in power generation. Total GHG emissions fell by an average of 1% per year between 1990 and 2000.

- **Recession in Former USSR:** The economic transition and the associated downturn during the period 1989 to 1998 saw fossil fuel related emissions fall by an average of 5.2% per year.

Source for emission figures: WRI (2006) and IEA (2006).

The key reason for the difficulty in sustaining a rapid rate of annual emissions cuts is inertia in the economy. This has three main sources:

- First, capital stock lasts a number of years and for the duration it is in place, it locks the economy into a particular emissions pathway, as early capital stock retirement is likely to be costly. The extent and impact of this is illustrated in Box 8.3.

- Second, developing new lower emissions technology tends to be a slow process, because it takes time to learn about and develop new technologies. This is discussed in more detail in Chapter 9.

---

[12] Zhu, Taylor, Feng (2004)

[13] Chapter 25 notes that some of this gain was offset by increased timber imports from outside China.

- Third, it takes time to change habits, preferences and institutional structures in favour of low-carbon alternatives. Chapter 15 discusses the importance of policy in shifting these.

These limits to the economically feasible speed of adjustment constrain the range of feasible stabilisation trajectories.

Box 8.4 The implications for mitigation policy of long-lived capital stock

Power generation infrastructure typically has a very long lifespan, as does much energy-using capital stock. Examples are given below.

Infrastructure	Expected lifetime (years)
Hydro station	75++
Building	45+++
Coal station	45+
Nuclear station	30 – 60
Gas turbine	25
Aircraft	25-35
Motor vehicle	12 - 20

Source: World Business Council for Sustainable Development (2004) and IPCC (1999).

This means that once an investment is made, it can last for decades. A high-carbon or low-efficiency piece of capital stock will tend to lock the economy into a high emissions pathway. The only options are then early retirement of capital stock, which is usually uneconomic; or “retrofitting” cleaner technologies, which is invariably more expensive than building them in from the start. This highlights the need for policy to recognise the importance of capital stock replacement cycles, particularly at key moments, such as the next two decades when a large volume of the world’s energy generation infrastructure is being built or replaced. Missing these opportunities will make future mitigation efforts much more difficult and expensive.

8.7 The Scale of the Challenge

Stabilisation at 550 ppm CO_2e requires emissions to peak in the next 10-20 years, and to decline at a substantial rate thereafter. Stabilisation at 450 ppm CO_2e requires even more urgent and strong action. But global emissions are currently on a rapidly rising trajectory, and under “business as usual” (BAU) will continue to rise for decades to come. The “mitigation gap” describes the difference between these divergent pathways.

To achieve stabilisation between 450 and 550 ppm CO_2e, the mitigation gap between BAU and the emissions path ranges from around 50 – 70 $GtCO_2$e per year by 2050.

Figure 8.4 plots expected trends in BAU emissions[14] against emission pathways for stabilisation levels in the range 450 to 550 ppm CO_2e. The exact size of the mitigation gap depends on assumptions on BAU trajectories, and the stabilisation level chosen. In this example, it ranges from around 50 to 70 $GtCO_2$e in 2050 to stabilise at 450 – 550 ppm CO_2e. For comparison, total global emissions are currently around 45 $GtCO_2$e per year.

Another way to express the scale of the challenge is to look at how the relationship needs to change between emissions and the GDP and population (two of the key drivers of emissions). To meet a 550 ppm CO_2e stabilisation pathway, global average emissions per capita need to fall to half of current levels, and emissions per unit of GDP need to fall to one quarter of current levels by 2050. These are structural shifts on a major scale.

Stabilising greenhouse gas concentrations in the range 450 – 550 ppm CO_2e will require substantial action from both developed and developing regions.

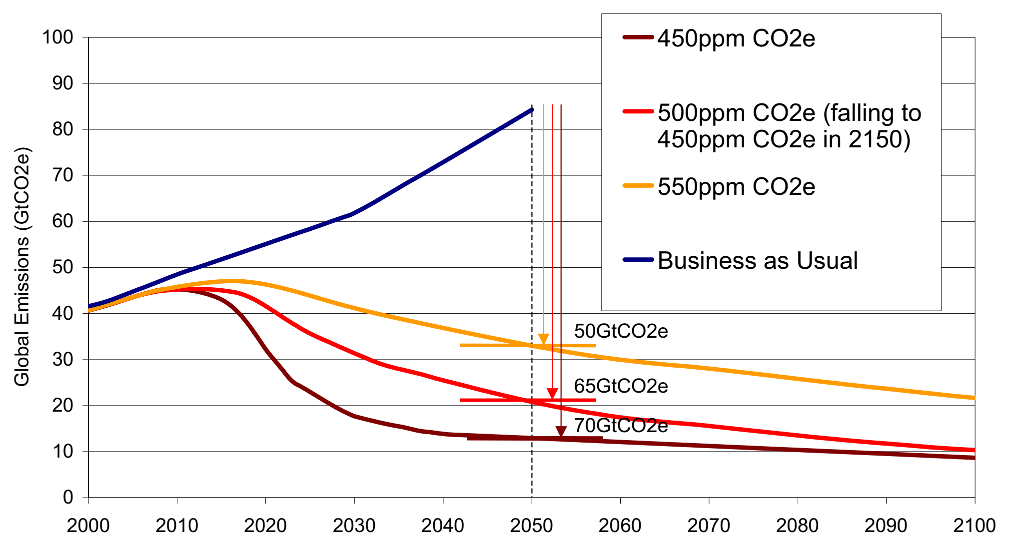
---

[14] Business as usual (BAU) used in this chapter is described in chapter 7.

Even if emissions from developed regions (defined in terms of Annex I countries[15]) could be reduced to zero in 2050, the rest of the world would still need to cut emissions by 40% from BAU to stabilise at 550 ppm CO_2e. For 450 ppm CO_2e, this rises to almost 80%. Emissions reductions in developed and developing countries are discussed further in Part VI.

Figure 8.4 BAU emissions and stabilisation trajectories for 450 - 550 ppm CO_2e

The figure below shows illustrative pathways to stabilise greenhouse gas levels between 450 ppm and 550 ppm CO_2e. The blue line shows a business as usual (BAU) trajectory. The size of the mitigation gap is demonstrated for 2050. To stabilise at 450 ppm CO_2e (without overshooting) emissions must be more than 85% below BAU by 2050. Stabilisation at 550 ppm CO_2e would require emissions to be reduced by 60 – 65% below BAU. Table 8.2 gives the reductions relative to 2005 levels.



Stabilisation at 550 ppm CO_2e or below is achievable, even with currently available technological options, and is consistent with economic growth.

An illustration of the extent and nature of technological change needed to make the transition to a low-carbon economy is provided by Socolow and Pacala (2004). They identify a 'menu' of options, each of which can deliver a distinct 'wedge' of savings of 3.7 $GtCO_2e$ (1 GtC) in 2055, or a cumulative saving of just over 90 $GtCO_2e$ (25 GtC) between 2005 and 2055. Each option involves technologies already commercially deployed somewhere in the world and no major technological breakthroughs are required. Some technologies are capable of delivering several wedges.

In their analysis, Socolow and Pacala only consider what effort is required to maintain carbon dioxide levels below 550 ppm (roughly equivalent to 610 – 690 ppm CO_2e when other gases are included) by implementing seven of their wedges. This is demonstrated in Figure 8.5.

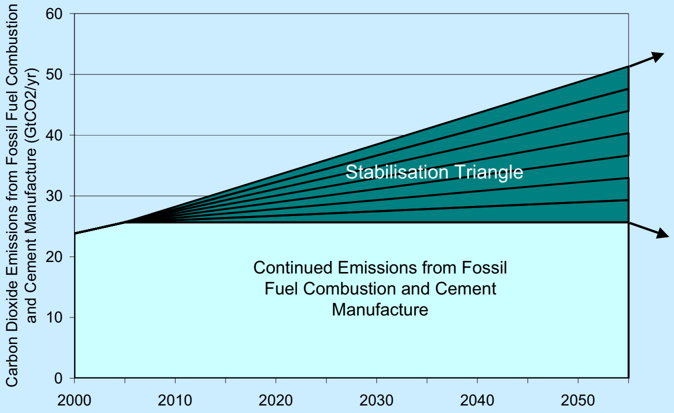
While the Socolow and Pacala analysis does not explicitly explore how to stabilise at between 450 and 550 ppm CO_2e, it does provide a powerful illustration of the scale of action that would be required. It demonstrates that substantial emissions savings are achievable with currently available technologies and the importance of utilising a mix of options across several sectors. These conclusions are supported by many other studies undertaken by industry, governments and the scientific and engineering research community.

---

[15] Annex I includes OECD, Russian Federation and Eastern European countries. This is discussed further in Part IV.

Figure 8.5 Socolow and Pacala's "wedges"

Socolow and Pacala compare a simple mitigation path for fossil fuel emissions with a projected BAU path. In the BAU path, fossil fuel CO_2 emissions grow to around 50 $GtCO_2e$ in 2055. In the mitigation path, fossil fuel CO_2 emissions remain constant at 25 $GtCO_2$ until 2055. This mitigation trajectory should maintain carbon dioxide concentrations at around 550 ppm. The difference between BAU and the stabilisation trajectory is the *stabilisation triangle*. To demonstrate how these emissions savings can be achieved, this triangle is split into 7 equal wedges, each of which delivers 3.7 $GtCO_2e$ (1 GtC) saving in 2055. Socolow and Pacala give a menu of fifteen measures that could achieve one wedge using currently available technologies. However, some wedges cannot be used together as they would double count emission savings. The panel to the right gives four of these suggested measures.



Four abatement measures that could each deliver one 'wedge' (3.7 $GtCO_2e$) in 2055.

1. Replace coal power with an extra 2 million 1-MW-peak windmills (50 times the current capacity) occupying $30*10^6$ ha, on land or off shore.
2. Increase fuel economy for all cars from 30 to 60 mpg in 2055.
3. Cut carbon emissions by one-fourth in buildings and appliances in 2055.
4. Replace coal power with 700GW of nuclear (twice the current capacity).

Source: Pacala and Socolow (2004)

To meet a stabilisation level of 550 ppm CO_2e or below, a broad portfolio of measures would be required, with non-energy emissions being a very important part of the story.

Fossil fuel related emissions from the energy sector in total would need to be reduced to below the current 26 $GtCO_2$ level, implying a very large cut from the BAU trajectory, which sees emissions more than doubling. This implies:

- A reduction in demand for emissions-intensive goods and services, with both net reductions in demand, and efficiency improvements in key sectors including transport, industry, buildings, fossil fuel power generation.
- The electricity sector would have to be largely decarbonised by 2050, through a mixture of renewables, CCS and nuclear.
- The transport sector is still likely to be largely oil based by 2050, but efficiency gains will be needed to keep down growth; biofuels, and possibly some hydrogen or electric vehicles could have some impact. Aviation is unlikely to see technology breakthroughs, but there is potential for efficiency savings.

A portfolio of technologies will be required to achieve this. Different studies make different assumptions on what the mix might be. This is discussed further in chapter 9.

Emissions from deforestation are large, but are expected to fall gradually over the next fifty years as forest resources are exhausted (Annex 7.F). With the right policies and enforcement mechanisms in place, the rate of deforestation could be reduced and substantial emissions cuts achieved. Together with policies on afforestation and reforestation, net emissions from land-use changes could be reduced to less than zero – that is, land-use change could strengthen natural carbon dioxide absorption.

Emissions from agriculture will rise due to rising population and income, and by 2020 could be almost one third higher than their current levels of 5.7 GtCO2e. The implementation of measures to reduce agricultural emissions is difficult, but there is potential to slow the growth in emissions.

In practice the policy choices involved are complex; some actions are much more expensive than others, and there are also associated environmental and social impacts and constraints.

The following chapters discuss how to achieve cost-effective emissions cuts over the next few decades. These activities must be continued and intensified to maintain stabilisation in the long run. Over the next few centuries, section 8.3 showed that emissions would need to be brought down to approximately the level of agriculture alone today. Given that preliminary analyses indicate that it would be difficult to cut agricultural emissions (chapter 9 and annex 7.F), this means that, in the long term, net emissions (which includes sequestration from activities such as planting forests) from all other sectors would need to fall to zero.

8.8 Conclusions

Stabilising the stock of greenhouse gases in the range 450 – 550 ppm CO_2e requires urgent, substantial action to reduce emissions, firstly to ensure that emissions peak in the next few decades and secondly, to make the rate of decline in emissions as low as possible. If insufficient action is taken now to reduce emissions, stabilisation will become more difficult in the longer term in terms of the speed of the transition required and the consequent costs of mitigation.

Stabilising greenhouse gas emissions is achievable through utilising a portfolio options, both technological and otherwise, across multiple sectors. The cost-effectiveness of these measures is discussed in detail in the following chapters.

References

The analyses of emissions trajectories presented in this chapter are based on those presented in den Elzen and Meinshausen (2005), using the same model (Meinshausen et al. 2006). These papers provide a clear and concise overview of the key issues associated with stabilisation paths. Pacala and Socolow (2004) discuss ways of filling the 'carbon gap' with currently available technologies.

Den Elzen, M. and M. Meinshausen (2005): 'Multi-gas emission pathways for meeting the EU 2°C climate target', in Schellnhuber et al. (eds.), Avoiding Dangerous Climate Change, Cambridge: Cambridge University Press.

Intergovernmental Panel on Climate Change (1999): 'Aviation and the global atmosphere', A Special Report of IPCC Working Groups I and III in collaboration with the Scientific Assessment Panel to the Montreal Protocol on Substances that Deplete the Ozone Layer [J.E. Penner, D.H. Lister, D.J. Griggs et al. (eds.)], Cambridge: Cambridge University Press.

International Energy Agency (2006): 'CO2 emissions from fossil fuel combustion on-line database', version 2005/06, Paris: International Energy Agency, available from http://data.iea.org/stats/eng/main.html

Jacobs, M. (1991): 'The green economy: Environment, sustainable development and the politics of the future, London: Pluto Press.

Jones, C.D., P.M. Cox and C. Huntingford (2006): 'Impact of climate-carbon feedbacks on emissions scenarios to achieve stabilisation', in Avoiding Dangerous Climate Change, Schellnhuber et al. (eds.), Cambridge: Cambridge University Press.

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', pp.265 – 280 in Avoiding dangerous climate change, H.J. Schellnhuber et al. (eds.), Cambridge: Cambridge University Press.

Meinshausen, M., D. van Vuuren, T.M.L. Wigley, et al. (2006): 'Multi-gas emission pathways to meet climate targets', Climatic Change, **75**: 151-194

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

O'Neill, B. and M. Oppenheimer (2004): 'Climate change impacts are sensitive to the concentration stabilization path'. Proceedings of the National Academy of Sciences **101(**47): 16411-16416

Pacala, S. and R. Socolow (2004): 'Stabilization wedges: Solving the climate problem for the next 50 years with current technologies', Science, **305**: 968-972

Prentice, I.C., G.D. Farquhar, M.J.R. Fasham, et al. (2001): 'The carbon cycle and atmospheric carbon dioxide', in Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [J. Houghton et al. (eds.)]. Cambridge: Cambridge University Press.

Ramaswamy, V. et al. (2001): 'Radiative forcing of climate change', in Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, [J. Houghton et al. (eds.)], Cambridge: Cambridge University Press.

US Climate Change Science Program (2006): 'Scenarios of greenhouse gas emissions and atmospheric concentrations and review of integrated scenario development and application', Public Review Draft of Synthesis and Assessment Product 2.1

Wigley, T.M.L. and S.C.B. Raper (2001): 'Interpretation of high projections for global-mean warming', Science **293**: 451-454

World Business Council for Sustainable Development (2004): 'Facts and trends to 2050 – energy and climate change', World Business Council for Sustainable Development, Stevenage: Earthprint Ltd., available from www.wbcsd.org

World Resources Institute (2006): Climate Analysis Indicators Tool (CAIT) on-line database version 3.0, Washington, DC: World Resources Institute, 2006, available from http://cait.wri.org

Zhu, C., R. Taylor and G. Feng (2004): 'China's wood market, trade and the environment', available from: http://assets.panda.org/downloads/chinawoodmarkettradeenvironment.pdf

9 Identifying the Costs of Mitigation

Key Messages

Slowly reducing emissions of greenhouse gasses that cause climate change is likely to entail some costs. Costs include the expense of developing and deploying low-emission and high-efficiency technologies and the cost to consumers of switching spending from emissions-intensive to low-emission goods and services.

Fossil fuel emissions can be cut in several ways: reducing demand for carbon-intensive products, increasing energy efficiency, and switching to low-carbon technologies. **Non-fossil fuel emissions are also an important source of emission savings**. Costs will differ considerably depending on which methods and techniques are used where.

- **Reducing demand for emissions-intensive goods and services is part of the solution.** If prices start to reflect the full costs of production, including the greenhouse gas externality, consumers and firms will react by shifting to relatively cheaper low-carbon products. Increasing awareness of climate change is also likely to influence demand. But demand-side factors alone are unlikely to achieve all the emissions reductions required.

- **Efficiency gains offer opportunities both to save money and to reduce emissions,** but require the removal of barriers to the uptake of more efficient technologies and methods.

- **A range of low-carbon technologies is already available, although many are currently more expensive than fossil-fuel equivalents.** Cleaner and more efficient power, heat and transport technologies are needed to make radical emission cuts in the medium to long term. Their future costs are uncertain, but experience with other technologies has helped to develop an understanding of the key risks. The evidence indicates that efficiency is likely to increase and average costs to fall with scale and experience.

- **Reducing non-fossil fuel emissions** will also yield important emission savings. The cost of reducing emissions from deforestation, in particular, may be relatively low, if appropriate institutional and incentive structures are put in place and the countries facing this challenge receive adequate assistance. Emissions cuts will be more challenging to achieve in agriculture, the other main non-energy source.

A portfolio of technologies will be needed. Greenhouse gases are produced by a wide range of activities in many sectors, so it is highly unlikely that any single technology will deliver all the necessary emission savings. It is also uncertain which technologies will turn out to be cheapest, so a portfolio will be required for low-cost abatement.

An estimate of resource costs suggests that the annual cost of cutting total GHG to about three quarters of current levels by 2050, consistent with a 550ppm CO_2e stabilisation level, will be in the range –1.0 to +3.5% of GDP, with an average estimate of approximately 1%. This depends on steady reductions in the cost of low-carbon technologies, relative to the cost of the technologies currently deployed, and improvements in energy efficiency. The range is wide because of the uncertainties as to future rates of innovation and fossil-fuel extraction costs. The better the policy, the lower the cost.

Mitigation costs will vary according to how and when emissions are cut. Without early, well-planned action, the costs of mitigating emissions will be greater.

9.1 Introduction

Vigorous action is urgently needed to slow down, halt and reverse the growth in greenhouse-gas (GHG) emissions, as the previous chapters have shown. This chapter considers the types of action necessary and the costs that are likely to be incurred.

This chapter outlines a conceptual framework for understanding the costs of reducing GHG emissions, and presents some upper estimates of costs to the global economy of reducing total emissions to three quarters of today's levels by 2050 (consistent with a 550ppm CO_2e stabilisation trajectory, described in Chapter 8). The costs are worked out by looking at costs of individual emission saving technologies and measures. Chapter 10 looks at what macroeconomic models can say about how much it would cost to reduce emissions by a similar extent, and reaches similar conclusions. Chapter 10 also shows why a 450ppm CO_2e target is likely to be unobtainable at reasonable cost.

Section 9.2 explains the nature of the costs involved in reducing emissions. Estimating the resource cost of achieving given reductions by adopting new de-carbonising technologies alone provides a good first approximation of the true cost. The costs of achieving reductions can be brought down, however, by sensible policies that encourage the use of a range of methods, including demand-switching and greater energy efficiency, so this approach to estimation is likely to exaggerate the true costs of mitigation.

Section 9.3 sets out the range of costs associated with different technologies and methods. The following four sections look at the potential and cost of tackling non-fossil fuel emissions (mainly from land-use change) and cutting fossil fuel related emissions (either by reducing demand, raising energy efficiency, or employing low-carbon technologies).

The overall costs to the global economy are estimated in Sections 9.7 and 9.8, using the resource-cost method. They are found to be in the region of –1.0 to 3.5% of GDP, with a central estimate of approximately 1% for mitigation consistent with a 550ppm CO_2e stabilisation level. Different modelling approaches to calculating the cost of abatement generate estimates that span a wide range, as Chapter 10 will show. But they do not obscure the central conclusion that climate-change mitigation is technically and economically feasible at a cost of around 1% of GDP.

While these costs are not small, they are also not high enough seriously to compromise the world's future standard of living. A 1% cost increase is like a one-off 1% increase in the price index with nominal income unaffected (see Chapter 10). While that is not insignificant, most would regard it as manageable, and it is consistent with the ambitions of both developed and developing countries for economic growth. On the other hand, climate change, if left unchecked, could pose much greater threats to growth, as demonstrated by Part II of this Review.

9.2 Calculating the costs of cutting GHG emissions

Any costs to the economy of cutting GHG emissions, like other costs, will ultimately be borne by households.

Emissions-intensive products will either become more expensive or impossible to buy. The costs of adjusting industrial structures will be reflected in pay and profits – with opportunities for new activities and challenges for old. The costs of adjusting industrial structures will be reflected in pay and profits – with opportunities for new activities and challenges for old. More resources will be used, at least for a while, in making currently emissions-intensive products in new ways, so fewer will be available for creating other goods and services. In considering how much mitigation to undertake, these costs should be compared with the future benefits of a better climate, together with the potential co-benefits of mitigation policies, such as greater energy efficiency and less local pollution, discussed in Chapter 12. The comparison is taken further in Chapter 13, where the costs of adaptation and mitigation are weighed up.

A simple first approximation to the cost of reducing emissions can be obtained by considering the probable cost of a simple set of technological and output changes that are likely to achieve those reductions.

One can measure the extra resources required to meet projected energy demand with known low-carbon technologies and assess a measures of the opportunity costs, for example, from forgone agricultural output in reducing deforestation. This is the approach taken below in Sections 9.7 and 9.8. If the costs were less than the benefits that the emissions reductions bring, it would be better to take the set of mitigation measures considered than do nothing. But there may be still better measures available[1].

The formal economics of marginal policy changes or reforms has been studied in a general equilibrium framework that includes market imperfections[2]. A reform, such as reducing GHG emissions by using extra resources, can be assessed in terms of the direct benefits of a marginal reform on consumers (the emission reduction and the reduced spending on fossil fuels), less the cost at shadow prices[3] of the extra resources.

The formal economics draws attention to two issues that are important in the case of climate-change policies. First, the policies need to bring about a large, or non-marginal, change. The marginal abatement cost (MAC) – the cost of reducing emissions by one unit – is an appropriate measuring device only in the case of small changes. For big changes, the marginal cost may change substantially with increased scale. Using the MAC that initially applies, when new technologies are first being deployed, would lead to an under-estimate of costs where marginal costs rise rapidly with the scale of emissions. This could happen, for example, if initially cheap supplies of raw materials start to run short. But it may over-estimate costs where abatement leads to reductions in marginal costs – for example, through induced technological improvements[4]. These issues will be discussed in more detail below, in the context of empirical estimates, where average and total costs of mitigation are examined as well as marginal costs.

It is important to keep the distinction between marginal and average costs in mind throughout, because they are likely to diverge over time. On the one hand, the marginal abatement cost should rise over time to remain equal to the social cost of carbon, which itself rises with the stock of greenhouse gases in the atmosphere (see Chapter 13). On the other hand, the average cost of abatement will be influenced not only by the increasing size of emissions reductions, but also by the pace at which technological progress brings down the total costs of any given level of abatement (see Box 9.6).

Second, as formal economics has shown, shadow prices and the market prices faced by producers are equal in a fairly broad range of circumstances, so market prices can generally be used in the calculations in this chapter. But an important example where they diverge is in the case of fossil fuels. Hydrocarbons are exhaustible natural resources, the supply of which is also affected by the market power of some of their owners, such as OPEC. As a result, the market prices of fossil fuels reflect not only the marginal costs of extracting the fuels from the ground but also elements of scarcity and monopoly rents, which are income transfers, not resource costs to the world as a whole. When calculating the offset to the global costs of climate-change policy from lower spending on fossil fuels, these rents should not be included[5].

---

[1] A full comparison of the cost estimates used in the Review is given in Annex 9A on www.sternreview.org.uk.

[2] See Drèze and Stern (1987 and 1990), Ahmad and Stern (1991) and Atkinson and Stern (1974).

[3] Expressed informally, shadow prices are opportunity costs: they can often be determined by 'correcting' market prices for market imperfections. For a formal definition, see Drèze and Stern (1987 and 1990). In the models used there, the extra resources for emissions reductions represent a tightening of the general equilibrium constraint and the shadow prices times the quantities involved represent a summary of the overall general equilibrium repercussions.

[4] Similar issues to those arising for marginal changes arise in assessing instruments for reducing GHG emission although in the non-marginal changes, the distributions of costs and benefits can be of special importance.

[5] Of course, if the objective is to calculate the costs of climate-change mitigation to energy users rather than to the world as a whole, the rents can be included.

If there are cheaper ways of reducing carbon emissions than the illustrative set of measures examined in this chapter, and there generally will be cheaper methods than any one particular set chosen by assumption, then the illustration gives an upper bound to total costs.

An illustration of how emissions can be reduced, and at what cost, by one particular simple set of actions should provide an over-estimate of the costs that will actually be involved in reducing emissions – as long as policies set the right incentives for the most cost-effective methods of mitigation to be used. Policy-makers cannot predict in detail the cheapest ways to achieve emission reductions, but they can encourage individual households and firms to find them. Thus the costs of mitigation will depend on the effectiveness of the policy tools chosen to deliver a reduction in GHG emissions. Possible tools include emission taxes, carbon taxation and tradable carbon quotas. Carbon pricing by means of any of these methods is likely to persuade consumers to reduce their spending on currently emissions-intensive products, a helpful channel of climate-change policy that is ignored in simple technology-based cost illustrations. Induced changes in the pattern of demand can help to bring down the total costs of mitigation, but consumers still suffer some loss of real income. Regulations requiring the use of certain technologies and/or imposing physical limits on emissions constitute another possible tool.

In assessing the impact of possible instruments, key issues include the structure of taxes and associated deadweight losses[6], the distribution of costs and benefits and whether or not they disrupt or enhance competitive processes. Some of these issues are tackled in simple ways by the model-based approaches to estimating costs of mitigation considered in Chapter 10. Chapter 14 considers the merits and demerits of different methods in further detail. That discussion also examines the notion of a 'double dividend' from raising taxes on 'public bads'. Chapter 11 uses UK input-output data to illustrate how extra costs proportional to carbon emissions would be distributed through the economy. If, for example, extra costs amounted to around \$30/tCO_2 (£70/tC), it would result in an overall increase in UK consumer prices of around 1%. The analysis shows how this additional cost would be distributed in different ways across different sectors.

In examining whether mitigation by any particular method should be increased at the margin, and whether policies are cost-effective, the concept of marginal abatement cost (MAC) is central. There are many possible ways to reduce emissions, and many policy tools that could be used to do so. The costs of reductions will depend on the method chosen. One key test of the cost effectiveness of a possible plan of action is whether the MAC for each method is the same, as it should be if total costs are to be kept to a minimum. Otherwise, a saving could be made by switching at the margin from an option with a higher MAC to one with a lower MAC. This principle should be borne in mind in the discussion of different abatement opportunities below.

9.3 The range of abatement opportunities

The previous section set out a conceptual framework for thinking about the costs of reducing GHG emissions. The following sections look in more detail at estimates of the costs of different methods of achieving reductions.

This section sets out four main ways in which greenhouse-gas emissions can be reduced. The first is concerned with abating non-fossil-fuel emissions, and the latter three are about cutting fossil-fuel (energy-related) emissions. These are:

- To reduce demand for emission-intensive goods and services
- To improve energy efficiency, by getting the same outputs from fewer inputs

---

[6] The deadweight loss to a tax on a good that raises \$1 of revenue arises as follows. Suppose the government has raised \$1 in tax revenue, and the consumer has paid this \$1 in tax. But, in addition, the individual has reduced consumption in response to changes in prices and the firms producing the goods have lost profits. In the jargon of economics, the sum of the loss of consumer surplus and the loss of producer surplus exceeds the tax revenue.

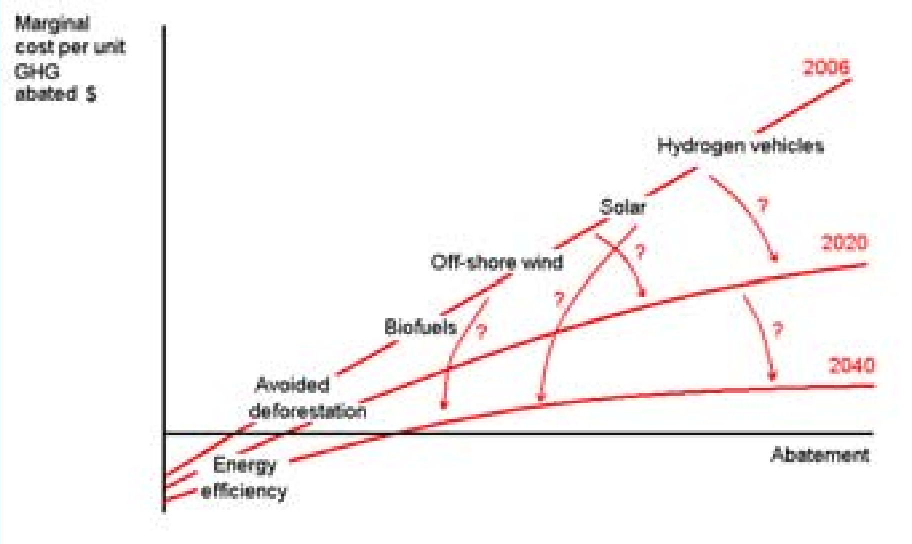
- To switch to technologies which produce fewer emissions and lower the carbon intensity of production
- To reduce non-fossil fuel emissions, particularly land use, agriculture and fugitive emissions

Annexes 7.B to 7.G[7] include some more detail on which technologies can be used to cut emissions in each sector, and the associated costs.

The array of abatement opportunities can be assessed in terms of their cost per unit of GHG reduction ($/tCO$_2$e), both at present and through time. In theory, abatement opportunities can be ranked along a continuum of the kind shown in Figure 9.1. This shows that some measures (such as improving energy efficiency and reducing deforestation) can be very cheap, and may even save money. Other measures, such as introducing hydrogen vehicles, may be a very expensive way to achieve emission reductions in the near term, until experience brings costs down.

The precise ranking of measures differs by country and sector. It may also change over time (represented in Figure 9.1 by arrows going from right to left), for example, research and development of hydrogen technology may bring the costs down in future (illustrated by the downward shift in the abatement curve over time).

Figure 9.1 Illustrative marginal abatement option cost curve



For any single technology, marginal costs are likely to increase with the extent of abatement in the short term, as the types of land, labour and capital most suitable for the specific technology become scarcer. The rate of increase is likely to differ across regions, according to the constraints faced locally.

For these reasons, flexibility in the type, timing and location of emissions reduction is crucial in keeping costs down. The implications for total costs of restricting this flexibility are discussed in more detail in Chapter 10. A test of whether there is enough flexibility is to consider whether the marginal costs of abatement are broadly the same in all sectors and countries; if not, the same amount of reductions could be made at lower cost by doing more where the marginal cost is low, and less where it is high.

---

[7] See www.sternreview.org.uk

9.4 Cutting non-fossil-fuel related emissions

Two-fifths of global emissions are from non-fossil fuel sources; there are opportunities here for low-cost emissions reductions, particularly in avoiding deforestation.

Non-fossil fuel emissions account for 40% of current global greenhouse-gas emissions, and are an important area of potential emissions savings. Emissions are mainly from non-energy sources, such as land use, agriculture and waste. Chapter 7 contains a full analysis of emission sources.

Almost 20% (8 $GtCO_2$/year) of total greenhouse-gas emissions are currently from deforestation. A study commissioned by the Review looking at 8 countries responsible for 70% of emissions found that, based upon the opportunity costs of the use of the land which would no longer be available for agriculture if deforestation were avoided, emission savings from avoided deforestation could yield reductions in CO_2 emissions for under \$5/tCO_2, possibly for as little as \$1/tCO_2 (see Box 9.1). In addition, large-scale reductions would require spending on administration and enforcement, as well as institutional and social changes. The transition would need to be carefully managed if it is to be effective.

Planting new forests (afforestation and reforestation) could save at least an additional 1 $GtCO_2$/yr, at a cost estimated at around \$5/tCO_2 - \$15/tCO_2[8]. The full technical potential of forestry related measures would go beyond this. An IPCC report in 2000 estimated a technical potential of 4 - 6 $GtCO_2$/year from the planting of new forests alone between 1995 and 2050, 70% of which would come from tropical countries[9]. Revised estimates are expected from the Fourth Assessment Report of IPCC.

Changes to agricultural land management, such as changes to tilling practices[10], could save a further 1 $GtCO_2$/year at a cost of around \$27/tCO_2e in 2020[11]. More recent analysis suggested savings could be as much as 1.8 $GtCO_2$ at \$20/tCO_2 in 2030[12]. The production of bioenergy crops would add further savings. In this chapter, this is discussed in the context of its application to emissions savings in other sectors (see Box 9.5). Biogas from animal wastes could also yield further savings.

---

[8] Benitez et al. (2005), using a land-cover database, together with econometric modelling and Sathaye et al. (2005).

[9] IPCC (2000) chapter 3.

[10] Conservation tillage describes tillage methods that leave sufficient crop residue in place to reduce exposure of soil carbon to microbial activity and hence, conserve soil carbon stocks (IPCC (2001)).

[11] IPCC (2001). Revised estimates are expected from the Fourth Assessment Report of IPCC.

[12] Smith et al (2006, forthcoming).

Box 9.1 The costs of reducing emissions by avoiding further deforestation

A substantial body of evidence suggests that action to prevent further deforestation would be relatively cheap compared with other types of mitigation.

Three types of costs arise from curbing deforestation. These are the opportunity cost foregone from preserving forest, the cost of administering and enforcing effective action, and the cost of managing the transition.

The opportunity cost to those who use the land directly can be estimated from the potential revenue per hectare of alternative land uses. These potential returns vary between uses. Oil palm and soya produce much higher returns than pastoral use, with net present values of up to \$2000 per hectare compared with as little as \$2 per hectare[13]. Timber is often harvested, particularly in South East Asia, where there is easy access to nearby markets and timber yields higher prices. Timber sales can offset the cost of clearing and converting land.

A study carried out for this Review[14] estimated opportunity costs on this basis for eight countries[15] that collectively are responsible for 70% of land-use emissions (responsible for 4.9 $GtCO_2$ today and 3.5 $GtCO_2$ in 2050 under BAU conditions). If all deforestation in these countries were to cease, the opportunity cost would amount to around \$5-10 billion annually (approximately \$1-2/tCO_2 on average). On the one hand, the opportunity cost in terms of national GDP could be higher than this, as the country would also forego added value from related activities, including processing agricultural products and timber. The size of the opportunity cost would then depend on how easily factors of production could be re-allocated to other activities. On the other hand, these estimates may overstate the true opportunity cost, as sustainable forest management could also yield timber and corresponding revenues. Furthermore, reducing emissions arising from accidental fires or unintended damage from logging may be lower than the opportunity costs suggest.

Other studies have estimated the cost of action using different methods, such as land-value studies assuming that the price of a piece of land approximates to the market expectation of the net present value of income from it, and econometric studies that estimate an assumed supply curve. In econometric studies[16], marginal costs have been projected as high as \$30t/CO_2 to eliminate all deforestation. High marginal values for the last pieces of forestland preserved are not inconsistent with a bottom-up approach based on average returns across large areas. These studies also suggest that costs are low for early action on a significant scale.

Action to address deforestation would also incur administrative, monitoring and enforcement costs for the government. But there would be significant economies of scale if action were to take place at a country level rather than on a project basis. Examination of such schemes suggests that the possible costs are likely to be small: perhaps \$12m to \$93m a year for these eight countries.

The policy challenges involved with avoiding further deforestation are discussed in Chapter 25.

The other main further sources of non-energy-related emissions, with estimates of economic potential for emissions reductions, are:

- Livestock, fertiliser and rice produce methane and nitrous oxide emissions. The IPCC (2001) suggested that around 1 $GtCO_2e$/year could be saved at a cost of up to \$27/tCO_2e[17] in 2020. However more recent analysis suggests that just 0.2

---

[13] These figures are calculated from income over 30 years, using a discount rate of 10%, except for Indonesia, which uses 20%.

[14] See Grieg-Gran report prepared for the Stern Review (2006)

[15] Cameroon, Democratic Republic of Congo, Ghana, Bolivia, Brazil, Papua New Guinea, Indonesia, Malaysia.

[16] See for example Sohngen et al (2006)

[17] IPCC (2001). Note this excludes savings from use of biomass and indirect emission reductions from fossil fuels via

$GtCO_2e$/year might be saved at \$20/tCO_2e in 2030[18]. It is important to investigate ways of cutting this growing source of emissions.

- Wastage in the production of fossil fuels (so-called fugitive emissions) and other energy-related non-CO_2 emissions currently amount to around 2 $GtCO_2e$/year[19]. If fugitive emissions of non-CO_2 and CO_2 gases could be constrained to current levels, then savings could amount to 2.3 $GtCO_2e$/year and 0.2 $GtCO_2$/year respectively in 2050 on baseline levels[20].

- Waste is currently responsible for 1.4 $GtCO_2e$/year[21], of which over half is from landfill sites and most of the remainder from wastewater treatment. Reusing and recycling lead to less resources being required to produce new goods and a reduction in associated emissions. Technologies such as energy-recovering incinerators also help to reduce emissions. The IPCC estimate that 0.7 $GtCO_2e$/year could be saved in 2020, of which three quarters could be achieved at negative cost and one quarter at a cost of \$5/tCO_2e[22].

- Industrial processes used to make products such as adipic and nitric acid produce non-CO_2 emissions; the IPCC estimate that 0.4 $GtCO_2e$/year could be reduced from these sources in 2020 at a cost of less than \$3/tCO_2e[23]. The production of products such as aluminium and cement also involve a chemical process that release CO_2. Assuming that emissions from this source could be reduced by a similar proportion, savings could amount to 0.5 $GtCO_2e$ in 2050[24].

Table 9.1 summarises the possible cost-effective non-fossil fuel CO_2 emission savings for 2050 described above. These figures are very uncertain but the estimates for waste and industrial processes arguably represent a lower-end estimate because they come from IPCC studies looking at possible emission savings in 2020, and savings by 2050 could be higher. Some of these savings cost \$5/tCO_2e or less, and it is possible that more could be saved at a slightly higher cost, with the technical potential for land-use changes being particularly significant. Achieving these emission savings would mean non-fossil fuel emissions in 2050 would be almost 11 $GtCO_2e$ lower in 2050 than in the baseline case.

---

energy-efficiency measures.

[18] Smith et al (2006 forthcoming).

[19] EPA (forthcoming).

[20] Stern Review estimates. This is consistent with a mitigation scenario in which fossil-fuel use is limited to current levels or below by 2050, as in the work by Dennis Anderson described later in this chapter, and the IEA (2006) analysis discussed in Section 9.9.

[21] EPA (forthcoming).

[22] IPCC (2001)

[23] IPCC (2001)

[24] Stern Review estimate.

Table 9.1 Non-fossil-fuel emissions, savings, and abatement costs by sector

Sector	BAU emissions in 2050 ($GtCO_2e$)[25]	Savings in 2050 ($GtCO_2e$)	Abatement scenario emissions in 2050 ($GtCO_2e$)
Deforestation (CO_2)	5.0	3.5	-0.5
Afforestation & reforestation (CO_2)		1.0	
Land-management practices (CO_2)		1.0	
Agriculture (non-CO_2)	18.8	1.0	14.3
Energy-related non-CO_2 emissions including fugitive emissions		2.3	
Waste (non-CO_2)		0.7	
Industrial processes (non-CO_2)		0.4	
Industrial processes (CO_2)	2.1	0.5	1.6
Fugitive emissions (CO_2)	0.4	0.2	0.2
Total	**26.3**	**10.7**	**15.6**

9.5 Reducing the demand for carbon-intensive goods and services

One way of reducing emissions is to reduce the demand for greenhouse-gas-intensive goods and services like energy. Policies to reduce the amount of energy-intensive activity should include creating price signals that reflect the damage that the production of particular goods and services does to the atmosphere. These signals will encourage firms and households to switch their spending towards other, less emissions-intensive, goods and services.

Regulations, the provision of better information and changing consumer preferences can also help. If people's preferences evolve as a result of greater sensitivity to energy use, for instance to favour smaller, more fuel-efficient vehicles, they may perceive the burden from 'trading down' from a larger vehicle as small or even negative (see Chapter 17). Efforts to reduce the demand for emissions-intensive activities include reducing over-heating of buildings, reducing the use of energy-hungry appliances, and the development and use of more environmentally friendly forms of transport.

In some cases, there may be 'win-win' opportunities (for example, congestion charging may lead to a reduction in GHG emissions and also reduce journey time for motorists and bus users). But some demand-reduction measures may conflict with other policy objectives. For example, raising the cost of private transport could lead to social exclusion, especially in rural areas. Chapter 12 discusses in more detail how climate change policy may fit with other policy objectives. Part IV of the Review includes discussion of how policy can be designed to ensure that the climate change damage associated with emission-intensive goods and services is better reflected in their prices.

9.6 Improving energy efficiency

Improving efficiency and avoiding waste offer opportunities to save both emissions and resources, though there may be obstacles to the adoption of these opportunities.

Energy efficiency refers to the proportion of energy within a fuel that is converted into a given final output. Improving efficiency means, for example, using less electricity to heat buildings to a given temperature, or using less petrol to drive a kilometre. The opportunities for reducing carbon emissions through the uptake of low-carbon energy sources, 'fuel switching', are not considered in this section.

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

---

[25] For explanation of how BAU emissions were calculated, see chapter 7.

the industrial countries. Hannah's historical study[26] of the UK electricity industry, for example, reports that the consumption of coal was 10-25 lbs/kWh in 1891, 5 lbs/kWh in the first decade of the 20th century and 1.5 lbs/kWh by 1947; today it is about 0.7 lbs/kWh[27], a roughly 10-fold increase over the century in the efficiency of power generation alone.

There have also been impressive gains in the efficiency with which energy is utilised for heating, lighting, refrigeration and motive power for industry and transport, with the invention of the fluorescent light bulb, the substitution of gas for coal for heat, the invention of double glazing, the use of 'natural' systems for lighting, heating and cooling, the development of heat pumps, the use of loft and cavity-wall insulation, and many other innovations.

Furthermore, the possibilities for further gains are far from being exhausted, and are now much sought after by industry and commerce, particularly those engaged in energy-intensive processes. Many of these opportunities are yet to be incorporated fully into the capital stock. For example, the full hybrid car (which may also pave a path for electric and fuel-cell vehicles) offers the prospect of a step change in the fuel efficiency of vehicles, while new diode-based technologies have the potential to deliver marked reductions in the intensity of lighting.

However, the rate of uptake of efficiency measures is often slow, largely because of the existence of market barriers and failures. These include hidden and transaction costs such as the cost of the time needed to plan new investments; a lack of information about the available options; capital constraints; misaligned incentives; together with behavioural and organisational factors affecting economic rationality in decision-making. These are discussed in more detail in Chapter 17.

There is much debate about how big a reduction in emissions efficiency measures could in practice yield. The IEA studies summarised in Section 9.9 find that efficiency in the use of fossil fuels is likely to be the single largest source of fossil fuel-related emission savings in 2050, capable of reducing carbon emissions by up to 16 $GtCO_2e$ per year by 2050. While estimates vary between studies, there is general agreement that the possibilities for further gains in efficiency are appreciable at each stage of energy conversion, across all sectors, end uses and economies.

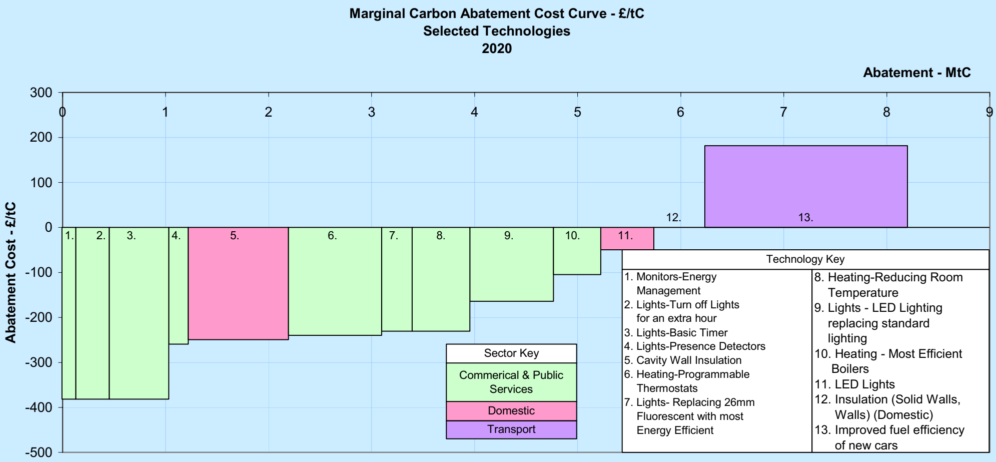
Figure 9.2 provides a graphical representation of the estimated costs and abatement potential by 2020 for a selected sample of energy efficiency technologies across different sectors.

---

[26] See Hannah (1979)

[27] Assuming 40% thermal efficiency and a c.v. of coal of 8,000kWh/tonne. Pounds (lbs) are a unit of weight: 1 lbs = 0.454 kg.

Figure 9.2 Aggregate carbon abatement cost curve for the UK – annual carbon savings by 2020[28]



Source: See notes

9.7 Low-carbon technologies

Options for low-emission energy technologies are developing rapidly, though many remain more expensive than conventional technologies.

This section examines the options for emissions reductions in the energy sector, their costs and how they are likely to move over time. The next section illustrates the costs of a set of policies in electricity and transport that could reduce emissions to levels consistent with a stabilisation path at 550ppm CO_2e. A range of options is currently available for decarbonising energy use in electricity generation, transport and industry, all of which are amenable to significant further development. These include:-

- On and offshore wind.
- Wave and tidal energy projects.
- Solar energy (thermal and photovoltaic).
- Carbon capture and storage for electricity generation (provided the risk of leakage is minimised) – Box 9.2 sets out the state of this relatively new technology, and what is known about costs.
- The production of hydrogen for heat and transport fuels.
- Nuclear power, if the waste disposal and proliferation issues are dealt with. A new generation of reactors is being built in India, Russia and East Asia. Reactors have either been commissioned or are close to being commissioned in France, Finland and the USA.
- Hydroelectric power, though environmental issues need to be considered and new sites will become increasingly scarce. The power output/storage ratio will also need to increase, to reduce the typical area inundated and increase the capacity of schemes to meet peak loads.
- Expansion of bioenergy for use in the power, transport, buildings and industry sectors from afforestation, crops, and organic wastes.

---

[28] This is intended to provide an indicative representation of average technology costs only (costs of individual technologies will, or course, vary). It draws together work on recent sectoral estimates undertaken by Enviros as part of the Energy Efficiency and Innovation Review (see www.defra.gov.uk/environment/energy/eeir/pdf/enviros-report.pdf) and drawing on data from the BRE and Enusim databases on the service sectors respectively, as well as Defra internal estimates for the domestic sector. The cost information presented here is based on a 3.5% social discount rate.

- Decentralised power generation, including micro-generation, combined heat and power (dCHP) using natural gas or biomass in the first instance, and hydrogen derived from low-carbon sources in the long term.
- Fuel cells with hydrogen as a fuel for transport (with hydrogen produced by a low-carbon method).
- Hybrid- and electric-vehicle technology (with electricity generated by a low-carbon method).

Box 9.2 Carbon capture and storage (CCS)

No single technology or process will deliver the emission reductions needed to keep climate change within the targeted limits. But much attention is focused on the potential of Carbon Capture and Storage (CCS). This is the process of removing and storing carbon emissions from the exhaust gases of power stations and other large-scale emitters. If it proved effective, CCS could help reduce emissions from the flood of new coal-fired power stations planned over the next decades, especially in India and China[29].

CCS technologies have the significant advantage that their large-scale deployment could reconcile the continued use of fossil fuels over the medium to long term with the need for deep cuts in emissions. Nearly 70% of energy production will still come from fossil fuels by 2050 in the IEA's ACT MAP scenario[30]. In their base case, energy production doubles by 2050 with fossil fuels accounting for 85% of energy. The growth of coal use in OECD countries, India and China is a particular issue – the IEA forecast that without action a third of energy emissions will come from coal in 2030. Even with strong action to encourage the uptake of renewables and other low-carbon technologies, fossil fuels may still make up to half of all energy supply by 2050. Successfully stabilising emissions without CCS technology would require dramatic growth in other low-carbon technologies.

Once captured, the exhaust gases can be either processed and compressed into liquefied CO_2 or chemically changed into solid, inorganic carbonates. Captured CO_2 can be transported either through pipelines or by ship. The liquid or solid CO_2 can be stored in various ways. As a pressurised liquid, CO_2 can also be injected into oil fields to raise well pressure and increase flow rates from depleted wells. Norway's Statoil, for example, captures emissions from on-shore power stations and re-injects the captured CO_2 for such 'enhanced oil recovery' from its off-shore Sleipner oil field.

In most cases, the captured gas will be injected and stored in suitable, non-porous underground rock foundations such as depleted oil and gas wells, deep saline formations and old coalmines. Other theoretically possible but as yet largely untested ways of storing the CO_2 are to dissolve it deep within the ocean, store as an inorganic carbonate or use the CO_2 to produce hydrogen or various carbon-rich chemicals. Careful site evaluation is needed to ensure safe, long-term storage. Estimates of the potential geological storage capacity range from 1,700 to 11,100 $GtCO_2$ equivalent[31], or from to 70 to 450 years of the 2003 level of fossil-fuel-related emissions (24.5 $GtCO_2$[32]/year).

It is technically possible to capture emissions from virtually any source, but the economics of CCS favours capturing emissions from large sources producing concentrated CO_2 emissions (such as power stations, cement and petrochemical plants), to capture scale economies, and where it is possible to store the CO_2 close to the emission and capture point, to reduce transportation costs.

There are several obstacles to the deployment of CCS, including technological and cost

---

[29] Read (2006) discusses how if CCS technologies were to capture emissions from the use of biofuels this could create negative emissions, that is, sequestering carbon dioxide from the atmosphere.

[30] IEA (2006) - ACT MAP is a scenario that includes CCS and where emissions are constrained to near-current levels in 2050 following a technology 'push' for low-carbon technologies.

[31] IPCC (2005)

[32] Page 93 IEA (2005)

barriers, particularly the need to improve energy efficiency in power stations adopting CCS. Others include regulatory and legal[33] barriers, such as the legal issues around the ownership of the CO_2 over long periods of time, the lack of safety standards and emission-recording guidelines. There are also environmental concerns that the CO_2 might leak or that building the necessary infrastructure might damage the local environment. Public opinion needs to be won over.

Employing CCS technology adds to the overall costs of power generation. But there is a wide range of estimates, partly reflecting the relatively untried nature of the technology and variety of possible methods and emission sources. The IPCC quotes a full range from zero to $270 per tonne of CO_2. A range of central estimates from the IPCC and other sources[34] show the costs of coal-based CCS employment ranging from $19 to $49 per tonne of CO_2, with a range from $22 to $40 per tonne if lower-carbon gas is used. Some studies provide current estimates and some medium-term costs. A range of technologies is also considered, with and without CCS, and some with more basic generation technologies as the baseline[35]. The assumptions set have an important impact on cost estimates. The range of cost estimates will narrow when CCS technologies have been demonstrated but, until this occurs, the estimates remain speculative.

The IPCC special report on CCS suggested that it could provide between 15% and 55% of the cumulative mitigation effort until 2100. The IEA's Energy Technology Perspectives uses a scenario that keeps emissions to near current levels by 2050, with 14 - 16.2% of electricity generated from coal-fired power stations using CCS. This would deliver from 24.7 - 27.6% of emission reductions[36]. Sachs and Lackner[37] calculate that, if all projected fossil-fuel plants were CCS, it could save 17 $GtCO_2$ annually at a cost of 0.1% to 0.3% of GDP[38], and reduce global emissions by 2050 from their 554ppm BAU to 508ppm CO_2.

IEA modelling shows that, without CCS, marginal abatement costs would rise from $25 to $43 per tonne in Europe, and from $25 to $40 per tonne in China, while global emissions are10% to 14% higher. This highlights the crucial role CCS is expected to play[39]. For more on international action and policies to encourage the demonstration and adoption of CCS technologies, see Section 24.3 and Box 24.8.

Most low-carbon technologies are currently more expensive than using fossil fuels.

Estimates of the costs per unit of energy of substituting low-carbon-emitting energy sources for fossil fuels over the next 10-20 years are presented in Box 9.3; the technologies shown cover electricity supply, the gas markets (mainly for heat) and transport. The costs are expressed as a central estimate, with a range.

---

[33] At present sub-sea storage of CO_2 without enhanced oil recovery would be illegal.

[34] Sources include MIT, SPRU, UK CCS, IPCC, UK Energy Review, Sachs and Lackner.

[35] Some compare CCGT, IGCC and supercritical/basic pulverised coal with and without CCS while others compare IGCC with CCS to pulverised coal without or an alternative fossil-fuel mix.

[36] At a cost of $0.9 trillion around $23 per tonne.

[37] Sachs and Lackner, 2005

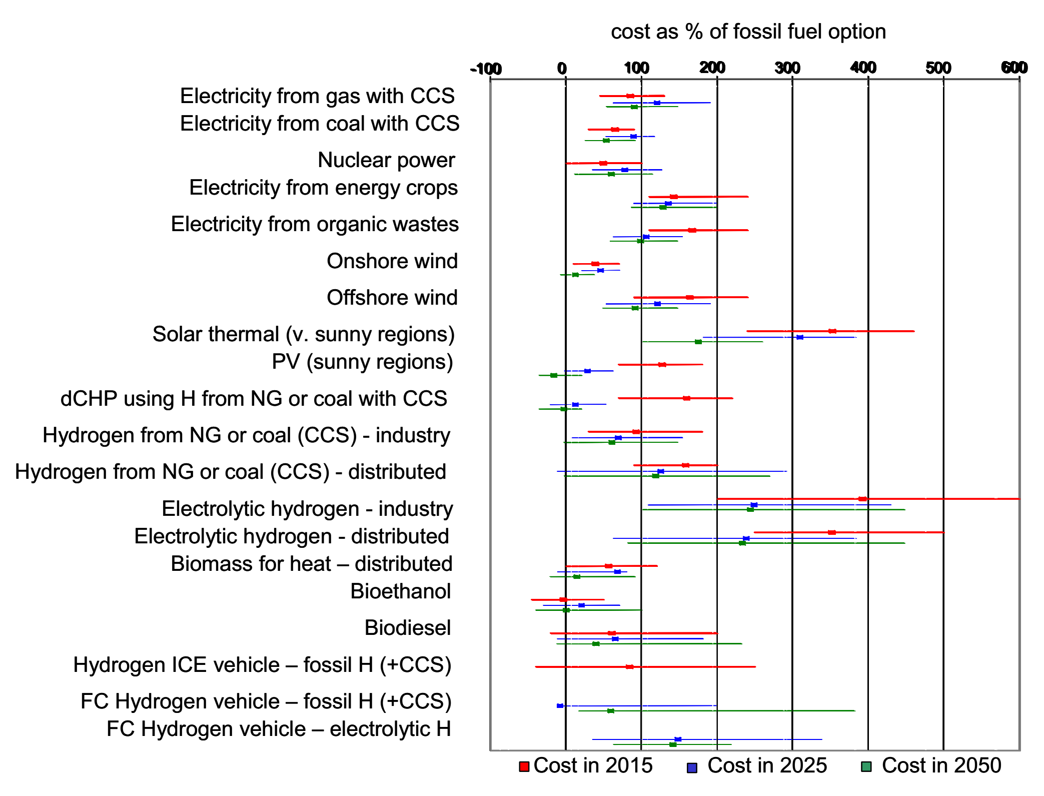
[38] $280 to $840 billion at $19 - $49/t$CO_2$.

[39] Page 61 IEA, 2006

Box 9.3 Costs of low-carbon technologies relative to fossil-fuel technologies replaced

This figure shows estimates by Anderson[40] of costs of technologies in 2015, 2025 and 2050 used to constrain fossil fuel emissions in 2050 at today's levels[41]. For most technologies, the unit cost as a proportion of the fossil-fuel alternative is expected to fall over time, largely because of learning effects (discussed below). But, as a technology comes up against increasing constraints and extends beyond its minimum efficient scale of production, the fall in unit costs may begin to reverse. The ranges quoted reflect judgements about the likely probability distribution for unit costs and allow for the variability of fossil-fuel prices (see text below and Section 9.8 for a further discussion of the treatment of uncertainties). The 0% line indicates that costs are the same as the corresponding fossil-fuel option.

Unit costs of energy technologies expressed as a percentage of the fossil-fuel alternative (in 2015, 2025, 2050)



Even in the near to medium term, the uncertainties are very large. The costs of technologies vary with their stage of development, and on specific regional situations and resource endowments, including the costs and availability of specific types of fossil fuels, the availability of land for bioenergy or sites for wind and nuclear power. Other factors include climatic suitability in the case of solar 'insolation' (incident solar energy) and concentrated emission sources (in the case of CCS). In recent years, oil prices have swung over a range of more than $50 per barrel and industrial gas from $4 to $9/GJ; such swings alone can shift the

---

[40] Paper by Dennis Anderson, "Costs and Finance of Carbon Abatement in the Energy Sector", published on the Stern Review web site.

[41] For central electricity generation, the cost ratios reflect the generation costs (including the capital costs of generation capacity), but exclude transmission and distribution. The costs of the latter are, however, included in the estimates for decentralised generation. The average costs of energy from the fossil-fuel technologies are 2.5p/kWh for central generation, 8p/kWh for decentralised generation, £4/GJ for industrial gas, $6/GJ for domestic gas, and 30p/litre (exclusive of excise taxes) for vehicle fuels; all are subject to the range of uncertainties noted in the text.

relative costs of the alternatives to fossil fuels by factors or two or three or more. In principle, estimates of global costs should be based on the extraction costs of fossil fuels, not their market prices, which include a significant but uncertain proportion of rents (see Section 9.2).

The cost of technologies tends to fall over time, because of learning and economies of scale.

Historical experience shows that technological development does not stand still in the energy or other sectors. There have been major advances in the efficiency of fossil-fuel use; similar progress can also be expected for low-carbon technologies as the state of knowledge progresses.

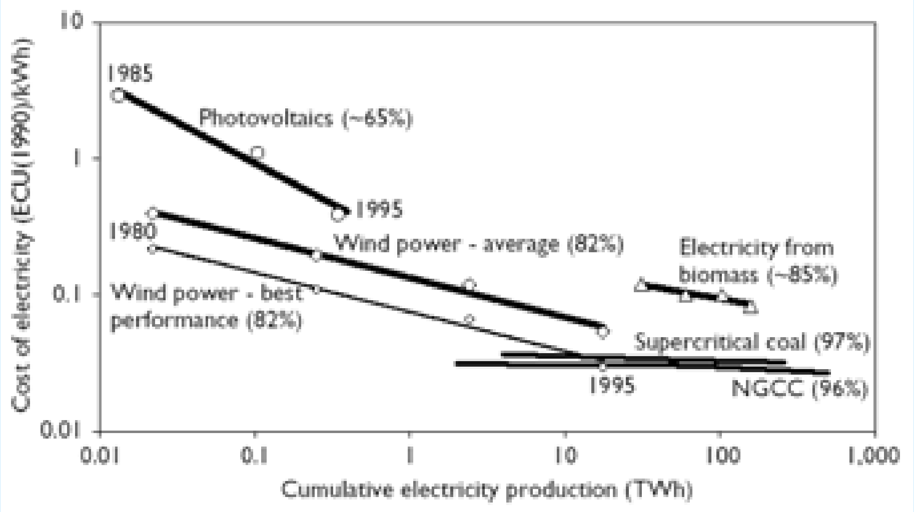
Box 9.4 shows cost trends for selected low-carbon technologies. Economists have fitted ‘learning curves’ to such data to estimate how much costs might decline with investment and operating experience, as measured by cumulative investment. ‘Learning’ is of course an important contributor to cost reductions, but should be seen as one aspect of several factors at work. These include:

- The development of new generations of materials and design concepts through R&D and the insights gained from investment and operating experience—for example, from current efforts to develop thin-film and organic solar cells, or in new materials and catalysts for fuel cells and hydrogen production and use;
- Opportunities for batch production arising from the modularity of some emerging technologies, such as solar PV. This leads to scale economies in production; to associated technical developments in manufacture; to the reduction of lead times for investments, often to a few months, as compared with three to six years or longer for conventional plant; and to the more rapid feedback of experience;
- R&D to seek further improvements and solve problems encountered with investments in place;
- Opportunities for scale economies in the provision of supporting services in installation and use of new technologies, the costs of which are appreciable when markets are small. For example, if specialised barges are required to install and service off-shore wind turbines, the equipment is much more efficiently utilised in a farm of 100 turbines than in one with just ten, and of course if there are many offshore wind farms in the project pipeline.

Box 9.4 Evidence on learning rates in energy technologies

A number of key energy technologies in use today have experienced cost reductions consistent with the theories of learning and scale economies. The diagram below shows historical learning rates for a number of technologies. The number in brackets gives an indication of the speed of learning: 97%, for instance, means that unit costs are 97% of their previous level after each doubling of installed capacity (3% cheaper).

Cost evolution and learning rates for selected technologies



Source: IEA (2000) pp21

After early applications in manufacturing and production (1930s) and business management, strategy and organisation studies, the past decade has seen the application of learning curves as an analytical tool for energy technologies (see IEA, 2000). The majority of published learning-rate estimates relevant to climate change relate to electricity-generation technologies. In Figure 9.5 above, estimates of learning rates from different technologies[42] span a wide range, from around 3% to over 35% cost reductions associated with a doubling of output capacity.

Using evidence on learning to project likely technology-cost changes suffers from selection bias, as technologies that fail to experience cost reductions drop out of the market and are then not included in studies. In order to correct for this, the learning and experience curves used to guide the cost exercise in this chapter take account of the high risks associated with new technologies. Moreover, the projected cost reductions are based on a far broader range of factors than just ‘learning’, as discussed in the main text.

The effects of the likely fall in costs with R&D and investment are reflected in the estimates for medium-term costs shown in Box 9.3. There is a general shift down in the expected costs of the alternatives to fossil fuels, in some cases to the point where they overlap under combinations of higher fossil-fuel prices and higher rates of technical progress.

In addition, the rankings of the technologies change, with some that are currently more expensive becoming cheaper with investment and innovation. Examples are solar energy in sunny regions and decentralised sources of combined heat and power (see Chapter 25). Nevertheless, most unit energy costs seem likely to remain higher than fossil fuels, and policies over the next 25 years should be based on this assumption. These are, of course, in the main costs borne in the first place by the private sector, although the public power sector is large in many countries. It will be the role of policy to shift the distribution of relative costs faced by investors in the low-carbon options downward relative to those of higher carbon options (see Part IV).

---

[42] Note different time periods for different technologies.

Costs, constraints and energy systems in the longer term

Moving to the longer term highlights the dangers of thinking in terms of individual technologies instead of energy systems. Most technologies can be expected to progress further and see unit costs reduced. But all will run into limitations that can be addressed only by developments elsewhere in the energy system. For example:

- *Energy Storage*. With the exception of biofuels, and hydrogen and batteries using low carbon energy sources, all the low carbon technologies are concerned with the instantaneous generation of electricity or heat. A major R&D effort on energy storage and storage systems will be crucial for the achievement of a low-carbon energy system. This is important for progress in transport, and for expanding the use of low-carbon technologies, for reasons discussed below.
- *Decarbonising transport.* The transport sector is still likely to remain oil-based for several decades, and efficiency gains will be important for keeping emissions down. Increasing use of biofuels will also be important (though see (iv) below). In the long term, decarbonising transport will also depend on progress in decarbonising electricity generation and on developments in hydrogen production. The main technological options currently being considered for decarbonising transport (other than the contributions of biofuels and efficiency) are hydrogen and battery-electric vehicles. Much will depend on transport systems too, including road pricing, intelligent infrastructure, public transport and urban design.
- *Nuclear power and base-load electricity generation*. A nuclear power plant is cheapest to operate continuously as base-load generation is expensive to shut down. There are possibilities of ‘load following’ from nuclear power, but this will reduce capacity utilisation and raise costs. Most of the load following (where output of the power plant is varied to meet the changes in the load) will be provided by fossil-fuel plant in the absence of investments in energy-storage systems. In addition, of course, there are issues of waste disposal and proliferation to be addressed
- *Intermittent renewables*. Renewables such as solar power and wind power only generate electricity when the natural resource is available. This leads to unpredictable and intermittent supply, creating a need for back-up generation. The cost estimates presented here allow for investment in and the fuel used in doing this, but, for high levels of market penetration, more efficient storage systems will be needed.
- *Bioenergy from crops*. Biomass can yield carbon savings in the transport, power generation, industry and building sectors. However exploitation of conventional biomass on a large scale could lead to problems of competition with agriculture for land and water resources, depending on crop practices and policies. This is discussed in Box 9.6.
- *The availability and long-term integrity of sites for carbon capture and storage*. This may set limits to the long-term contribution of CCS to a low-carbon economy, depending on whether alternative ways of storing carbon are discovered in time. It nevertheless remains an important option given the continued use of cheap fossil fuels, particularly coal, over the coming decades
- *Electricity and gas infrastructure*. Infrastructure services and their management would also change fundamentally with the emergence of small-scale decentralised generation and CHP, and with hydrogen as an energy-carrying and storage medium for the transport and heat markets. There will also be new opportunities for demand management through new metering and information and control technologies.

Box 9.5 Biomass: emission saving potential and costs

Biomass, the use of crops to produce energy for use in the power generation, transport, industry and buildings sectors, could yield significant emission savings in the transport, power and industry sectors. When biomass is grown, it absorbs carbon from the atmosphere during the photosynthesis process; when the crop is burnt, the carbon is released again. Biomass is not a zero carbon technology because of the emissions from agriculture and the energy used in conversion. For example, when used in transport, emissions savings from biofuel vary from 10-90% compared to petrol depending on the source of biofuel and production technique used.

Biomass crops include starch and sugar crops such as maize and sugar cane, and oil crops such as sunflower, rapeseed and palm oil. These biocrops are often referred to as first generation biomass because the technologies for converting them into energy are well developed. The highest yielding biocrops tend to be water-intensive and require good quality land, but some other biocrops can be grown on lower quality land with little water.

Research is now focusing on finding ways of converting lignocellulosic materials (such as trees, grasses and waste materials) into energy (so-called second generation technology).

The technical potential of biomass could be very substantial. On optimistic assumptions, the total primary bioenergy potential could reach 4,800-12,000 Mtoe by 2050[43] (compared with anticipated energy demand under BAU conditions of 22,000 Mtoe in 2050). Half of the primary biomass would come from dedicated cropland and half would be lignocellulosic biomass (residues and waste converted into energy). 125-150 million ha would be required for biomass crops (10% of all arable land worldwide, roughly the size of France and Spain together). However this analysis does not take into account the potentially significant impacts on local environment, water and land resources, discussed in Section 12.6. The extent to which biomass can be produced sustainably and cost effectively will depend on developments in lignocellulosic technology and to what extent marginal and low-quality land is used for growing crops.

The economically viable potential for biomass is somewhat smaller, and has been estimated at up to 2,600 Mtoe, almost a tripling of current biomass use. According to the IEA, this would result in an emission reduction of 2 to 3 $GtCO_2e$/year on baseline levels by 2050 at \$25/tCO_2 (though the actual estimate can vary widely around this depending on oil prices). If it is assumed that one-third of biomass were used for transport fuels by 2050, for example, it could meet 10% of road transport fuel demand, compared with 1% now. This could grow to 20% under more optimistic assumptions. Biomass costs vary both by crop and by country; current production costs are lowest in parts of Southern and Central Africa and Latin America.

This analysis excludes the possible emission savings from biogas (methane and CO_2 collected from decomposing manure). This technology is discussed in Box 17.7.

These limitations mean that all technologies will run into increasing marginal cost as their uptake expands, which will offset to some extent the likely reductions in cost as developments in the technology occur. Some of the constraints might be removed – research is ongoing, for example, on storing carbon in solid form (see Box 9.2). On the other hand, economies of scale and induced innovation will serve to bring down costs. Overall, a phased use of technologies across the board is likely to limit the cost burden of mitigating and sequestering GHGs.

In the current and next generation of investments over the next 20 years, the costs of climate change mitigation will probably be low, as some of the more familiar and easier options are exploited first. But as the scale of mitigation activities expands, at some point the problems posed by storage and the need to develop new systems and infrastructures must be

---

[43] All the emission saving and cost estimates in this box come from IEA analysis. IEA (2006) and IEA (in press).

overcome, particularly to meet the needs of transport. This is expected to raise costs (see below).

When looking forward over a period of several decades, however, there is also significant scope for surprises and breakthroughs in technology. This is one of the reasons why it is recommended that R&D and demonstration efforts are increased, both nationally and internationally (see discussion in Chapters 16 and 24). Such surprises may take the form of discoveries and innovations not currently factored into mainstream engineering analysis of energy futures[44].

The conclusion to be drawn from the analysis of the costs and risks associated with developing the various technologies, from the uncertainties as to their rates of development, and from the known limitations of each, is that no single technology, or even a small subset of technologies, can shoulder the task of climate-change mitigation alone. If carbon emissions are to be reduced on the scale shown to be necessary for stabilisation in Chapter 8, then policies must encourage the development of a portfolio of options; this will act both to reduce risks and improve the chances of success. Chapter 16 of this Review discusses how this can be done.

9.8 A technology-based approach to costing mitigation of fossil fuel emissions

This section presents the results of calculations undertaken for this review by Dennis Anderson[45]. It illustrates how fossil-fuel (energy) emissions could be cut from 24 $GtCO_2e$/year in 2002 to 18 $GtCO_2e$/year in 2050 and how much this would cost. Together with the non-fossil fuel savings outlined in Table 9.1, this would be consistent with a 550ppm CO_2e stabilisation trajectory in 2050 (outlined in Chapter 8).

A key advantage of this exercise is that it is data-driven, transparent, and easy to understand. It builds on the analysis of options in the preceding section. It illustrates one approach and establishes a benchmark. This will lead to an upward bias in the estimated costs, as there are many options, some of which will appear along the way with appropriate R&D, which will be cheaper. Like any such exercise, however, it depends on its assumptions. An independent technology-based study has recently been carried out by the IEA (see Section 9.9), which comes up with rather lower cost estimates. The next chapter reviews studies based on an economy-wide approach that attempt to incorporate some economic responses to policy instruments. These are broadly consistent with the results presented here.

The exercise here assumes that energy-related emissions at first rise and are then reduced to 18 $GtCO_2$/year through a combination of improvements in energy efficiency and switching to less emission-intensive technologies. This calculation looks only at fossil fuel related CO_2 emissions, and excludes possible knock-on effects on non-fossil fuel emissions. The precise approach used and assumptions made are detailed in the full paper[46].

Figure 9.3 presents the estimated BAU[47] energy-related CO_2 emissions over the period to 2075 and the abatement trajectory associated with reducing emissions to reach current levels by 2050. The abatement trajectory demonstrates a peak in emissions at 29 $GtCO_2$/year in 2025 before falling back to 18 $GtCO_2$/year in 2050, and falling further to reach 7 $GtCO_2$/year in 2075.

---

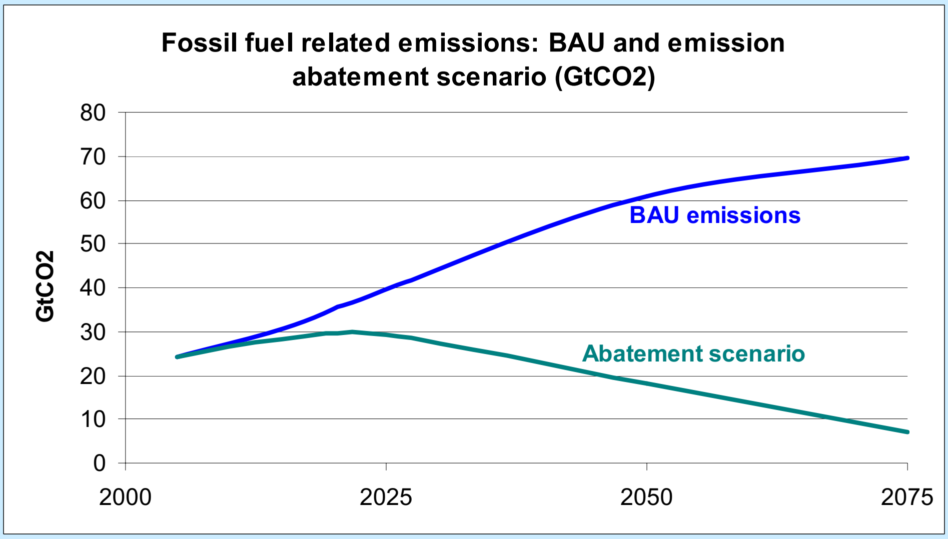
[44] Examples might be polymer-based PVs, with prospects for ‘reel-to-reel’ or batch processing; the generation of hydrogen directly from the action of sunlight on water in the presence of a catalyst (photo-electrolysis); novel methods and materials for hydrogen storage; small and large-scale energy storage devices more generally, including one known as the regenerable fuel cell; nuclear fusion; and new technologies and practices for improving energy efficiency. In addition, the technologies currently under development will also offer scope for ‘learning-by-doing’ and scale economies in manufacture and use.

[45] Dennis Anderson is Emeritus Professor of Energy and Environmental Studies at Imperial College London, and was formerly the Senior Energy Adviser and an economist at the World Bank, Chief Economist of Shell and an engineer in the electricity supply industry.

[46] Paper by Dennis Anderson, published on the Stern Review web site, ”Costs and Finance of Carbon Abatement in the Energy Sector.”

[47] This analysis assumes that fossil fuels emissions reach 61 $GtCO_2$/year in 2050 under BAU conditions. Note this is slightly greater than the BAU projection of fossil fuel emissions used in chapter 8 and parts of chapter 7 (of 58 $GtCO_2$/year in 2050).

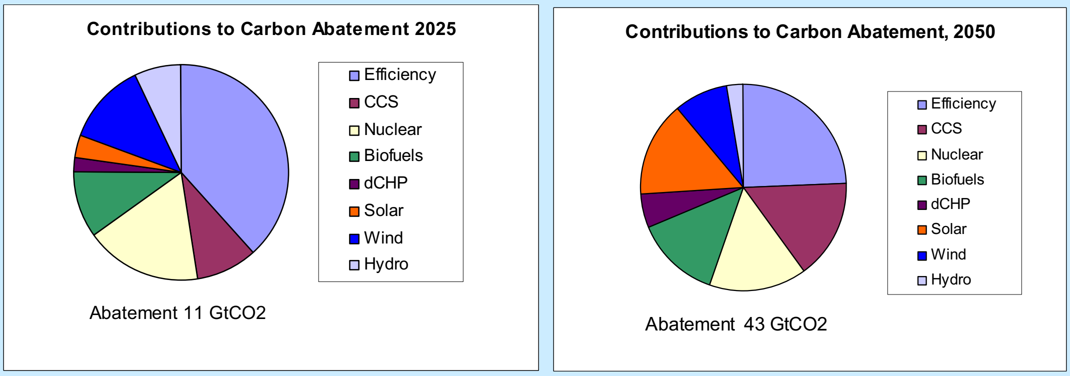
Figure 9.3 Emissions scenarios



A combination of technologies, together with advances in efficiency, are needed to meet the stabilisation path.

For each technology, assumptions are made on plausible rates of uptake over time[48]. It is assumed, for the purposes of simplification, that as the rate of uptake of individual technologies is modest, they will not run into significant problems of increasing marginal cost (as discussed above in Section 9.7). Assumptions are also made on the potential for energy-efficiency improvements. These assumptions can be used to calculate an average cost of abatement. Estimates of the additional contribution of energy efficiency and technological inputs to abatement are shown in Figure 9.4. The implications for sources of electricity and composition of road transport vehicle fleet are illustrated in the full paper.

Figure 9.4 The distribution of emission savings by technology

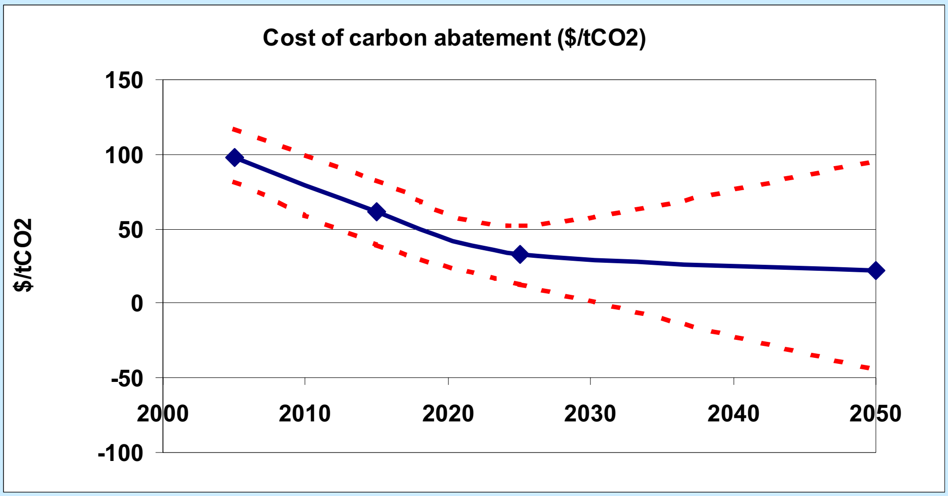


An average cost of abatement per tonne of carbon can be constructed by calculating the cost of each technology (as in Box 9.3) weighted by the assumed take-up, and comparing this with the emissions reductions achieved by these technologies against fossil-fuel alternatives. This is shown in Figure 9.5, where upper and lower bounds represent best estimates of 90% confidence intervals.

---

[48] More detail on the assumptions made can be found in Anderson (2006).

Figure 9.5 Average cost of reducing fossil fuel emissions to 18 $GtCO_2$ in 2050*



*The red lines give uncertainty bounds around the central estimate. These have been calculated using Monte Carlo analysis. For each technology, the full range of possible costs (typically ± 30% for new technologies, ±20% for established ones) is specified. Similarly, future oil prices are specified as probability distributions ranging from $20 to over $80 per barrel, as are gas prices (£2-6/GJ), coal prices and future energy demands (to allow for the uncertain rate of uptake of energy efficiency). This produces a probability distribution that is the basis for the ranges given.

The costs of carbon abatement are expected to decline by half over the next 20 years, because of the factors discussed above, and then by a third further by 2050. But the longer-term estimates of shifting to a low-carbon energy system span a very broad range, as indicated in the figure, and may even be broader than indicated here. This reflects the inescapable uncertainties inherent in forecasting over a long time period, as discussed above. It should be noted that, although average costs may fall, marginal costs are likely to be on a rising trajectory through time, in line with the social cost of carbon; this is explained in Box 9.6.

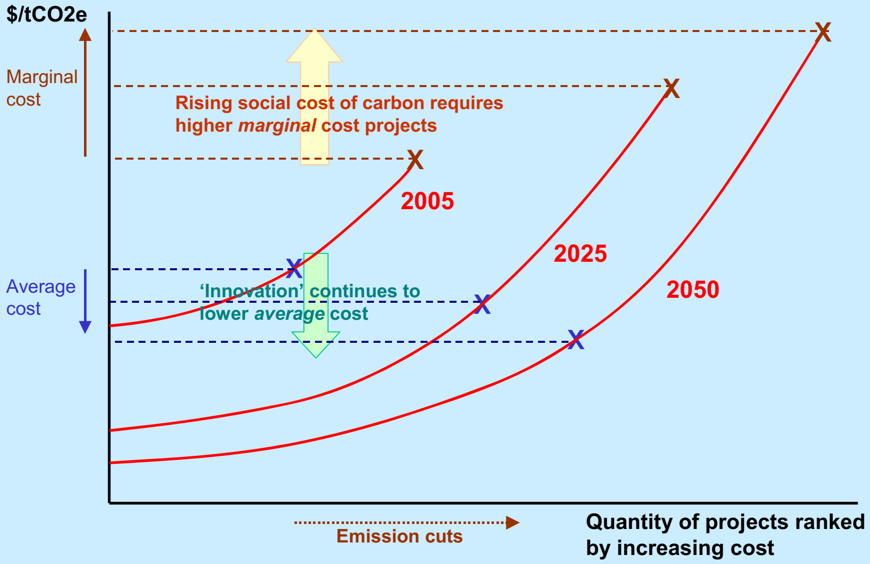
Box 9.6 The relationship between marginal and average costs over time

It is important not to confuse average costs with marginal costs or the prevailing carbon price. The carbon price should reflect the social cost of carbon and be rising with time, because of increased additional damages per unit of GHG at higher concentrations of gases in the atmosphere (see Chapter 13). Rising prices should encourage abatement projects with successively higher marginal costs. This does not necessarily mean that the average costs will rise. Indeed, in this analysis, average costs are assumed to fall, quickly at first and then tending to level off (Figure 9.5). At any time, marginal costs will tend to be above average costs as the most costly projects are undertaken last.

At the same time, however, innovation, learning and experience – driven through innovation policy – will lower the cost of producing any given level of output using any specific technology. This is shown in the figure below, which traces the costs of a specific technology through time.

Despite more extensive use of the technology and rising costs on the margin through time (reflecting the rising carbon price), the average cost of the technology may continue to fall. The key point to note is that marginal costs might be rising even where average costs are falling (or at least rising more slowly), as a growing range of technologies are used more and more intensively.

Illustrative cost per unit of GHG abated for a specific technology



The global cost of reducing total GHG emissions to three quarters of current levels (consistent with 550ppm CO_2e stabilisation trajectory) is estimated at around $1 trillion in 2050 or 1% of GDP in that year, with a range of –1.0% to 3.5% depending on the assumptions made.

Anderson's central case estimate of the total cost of reducing fossil fuel emissions to around 18 $GtCO_2e$/year (compared to 24 $GtCO_2$/year in 2002) is estimated at $930bn, or less than 1% of GDP in 2050 (see table 9.2). In the analysis by Anderson, this is associated with a saving of 43 $GtCO_2$ of fossil fuel emissions relative to baseline, at an average abatement cost of $22/$tCO_2$/year in 2050. However these costs vary according to the underlying assumptions, so these are explored below.

Table 9.2 Annual total costs of reducing fossil fuel emissions to 18 $GtCO_2$ in 2050

	2015	2025	2050
Average cost of abatement, \$/t CO_2	61	33	22
Emissions Abated $GtCO_2$ (relative to emissions in BAU)	2.2	10.7	42.6
Total cost of abatement, \$ billion per year:	134	349	930

The sensitivity of the cost estimates to different assumptions is presented in Table 9.3[49]; costs are shown as a percentage of world product. Over the next 20 years, it is virtually certain that the costs of providing energy will rise with the transition to low-carbon fuels, barring shocks in oil and gas supplies. Over the longer term, the estimates are less precise and, as one would expect, are sensitive to the future prices of fossil fuels, to assumptions as to energy efficiency, and indeed to the prices of the low-carbon technologies, such as carbon capture and storage.

Overall, the estimates range from -1.0% (a positive contribution to growth) to around 3.5% of world product by 2050, and are within the range of a large number of other studies discussed below in the next chapter. The estimates fan out in precisely the same way as those for the costs per tonne of carbon abatement shown in Figure 9.5, and for precisely the same reasons[50].

Table 9.3 Sensitivity analysis of global costs of cutting fossil fuel emissions to 18 $GtCO_2$ in 2050 (costs expressed as % of world GDP) [a]

Case	2015	2025	2050
(i) Central case	0.3	0.7	1.0
(ii) Pessimistic technology case	0.4	0.9	3.3
(iii) Optimistic technology case	0.2	0.2	-1.0
(iv) Low future oil and gas prices	0.4	1.1	2.4
(v) High future oil and gas prices	0.2	0.5	0.2
(vi) High costs of carbon capture and storage	0.3	0.8	1.9
(vii) A lower rate of growth of energy demand	0.3	0.5	0.7
(viii) A higher rate of growth of energy demand	0.3	0.6	1.0
(ix) Including incremental vehicle costs[b]			
• Means	0.4	0.8	1.4
• Ranges	0.3-0.5	0.5-1.1	-0.6- 3.5

[a] The world product in 2005 was approximately \$35 trillion (£22 trillion at the PPP rate of \$1.6/£). It is assumed to rise to \$110 trillion (£70 trillion) by 2050, a growth rate of 2.5% per year, or 1 ½ -2% in the OECD countries and 4-4½% in the developing countries.

[b] Assuming the incremental costs of a hydrogen fuelled vehicle using an internal combustion engine are £2,300 in 2025 and \$1400 in 2050, and for a hydrogen fuelled fuel cell vehicle £5000 in 2025 declining to £1700 by 2050. (Ranges of ~ ± 30% are taken about these averages for the fuel cell vehicle.)

Assumptions as to future oil and gas prices and rates of innovation clearly make a large difference to the estimates. Combinations of a return to low oil and gas prices and low rates of innovation lead to higher costs, while higher oil and gas prices and rates of innovation point to possibly beneficial effects on growth (even ignoring the benefits of climate change mitigation). Another cost, which requires attention, is the incremental cost of hydrogen vehicles (case ix). Costly investment in hydrogen cars would significantly increase the costs associated with this element of mitigation. However, in so far as such costs might induce a switch out of mitigation in the transport sector towards alternatives with lower MACs, these estimates are likely to overstate the true cost impact on the whole economy.

The fossil fuel emission abatement costs outlined in table 9.2 together with the non-fossil fuel emission savings presented in Table 9.1 would be sufficient to bring global GHG emissions to

---

[49] A full specification of the different cases are set out in the full paper.

[50] Rows (ii) and (iii) provide a rough estimate of the confidence intervals associated with the estimates in row (i).

around 34 $GtCO_2e$ in 2050, which is consistent with a 550ppm CO_2e stabilisation trajectory. The cost of this is estimated at under $1 trillion in 2050 (or 1% of GDP in that year).

In absolute terms, the costs are high, but are within the capacity of policies and industry to generate the required financial resources. For the economy as a whole, a 1% extra cost would be like a one-off increase in the price index by one percentage point (with unchanged nominal income profiles), although the impact will be significantly more for energy-intensive sectors (see Chapter 11). Economies have in the past dealt with much more rapid changes in relative prices and shocks from exchange-rate changes of much larger magnitude.

9.9 Other technology-based studies on cost

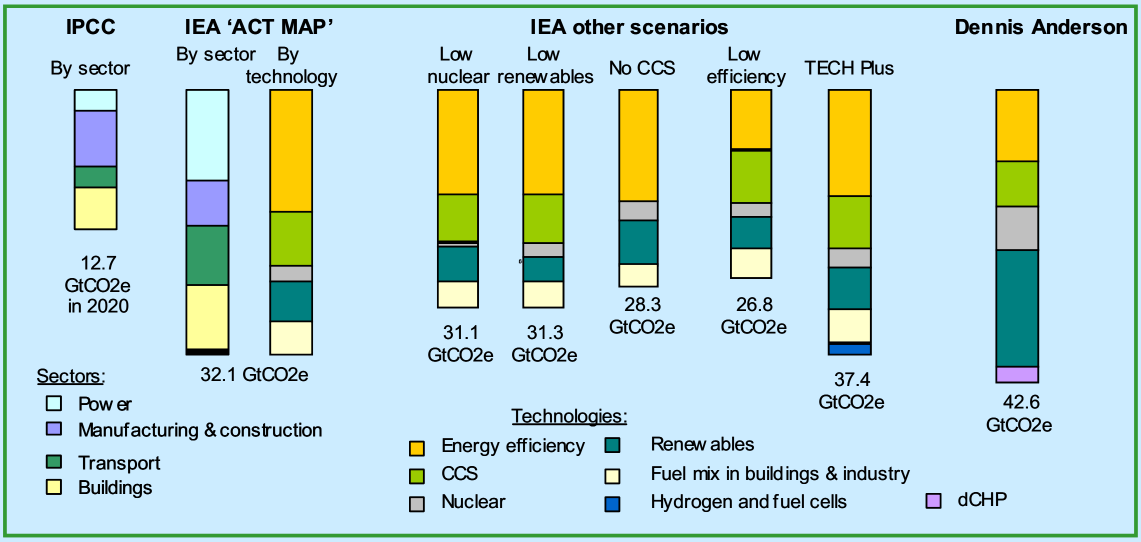
Other modellers have also taken a technology-based approach to looking at emissions reductions and costs. The IEA, in particular, have done detailed work based on their global energy models on the technological and economic feasibility of cutting emissions below business as usual, while also meeting other energy-policy goals.

The recent Energy Technology Perspectives report (2006) looks at a number of scenarios for reducing energy-related emissions from baseline levels by 2050. Scenarios vary in their assumptions about factors such as rates of efficiency improvements in various technologies. Box 9.7 sets out the scenarios in the report, and compares this with work by the IPCC, as well as the technology-based estimates by Anderson set out in this chapter.

These studies make different assumptions about the quantity of abatement achieved, and the exact mix of technologies and efficiency measures used to achieve this. But all agree on some basic points. These are that energy efficiency will make up a very significant proportion of the total; that a portfolio of low-carbon technologies will be needed; and that CCS will be particularly important, given the continued use in fossil fuels.

The report also looks at the additional costs for the power-generation sector of achieving emissions cuts. It finds that in the main alternative policy scenario (‘ACT MAP’), which brings energy-related emissions down to near current levels by 2050, additional investments of $7.9 trillion would be needed over the next 45 years in low-carbon power technologies, compared with the baseline scenario. However, there would be $4.5 trillion less spent on fossil-fuel power plants, in part because of lower electricity demand due to energy-efficiency improvements. In addition, there would be significant savings in transmission and distribution costs, and fuel costs; taking these into account brings the total net cost to only $100bn over 45 years.

Box 9.7 Sources of fossil fuel related emission savings in 2050



The bars in the diagram above show the composition of emissions reductions achieved in different models. The IPCC work relates to emissions savings in 2020, while the others relate to emissions savings in 2050. Separately, the IPCC have also estimated plausible emissions savings from non-energy sectors (discussed in Section 9.4).

The IPCC reviewed studies on the extent to which emissions could be cut in the power, manufacturing and construction, transport and buildings sectors. They find that for a cost of less than $25/tCO$_2$e, emissions could be cut by 10.8 - 14.7 GtCO$_2$e in 2020. The savings presented in the diagram are around the mid-point of this range.

The IEA Energy Technology Perspectives report sets out a range of scenarios for reducing energy-related CO$_2$ emissions by 2050, based on a marginal abatement cost of $25/tCO$_2$ in 2050, and investment in research and development of new technologies. The 'ACT MAP' scenario is the central scenario; the others make different assumptions on, for instance, the success of CCS technology and the ability to improve energy efficiency. Total emission savings range from 27 to 37 GtCO$_2$/year. In all scenarios, the IEA find that the CO$_2$ intensity of power generation is half current levels by 2050. However there is much less progress in the transport sector in all scenarios apart from TECH PLUS because further abatement from transport is too expensive. To achieve further emission cuts beyond 2050, transport would have to be decarbonised.

The forthcoming World Energy Outlook (2006) depicts an Alternative Policy Scenario that shows how the global energy market could evolve if countries were to adopt all of the policies they are currently considering related to energy security and energy-related CO$_2$ emissions. This Alternative Policy Scenario cuts fossil fuel emissions by more than 6 GtCO$_2$/year against the Reference Scenario by 2030, and finds that there is little difference in the investment requirements[51]. The World Energy Outlook (2006) also looks at a more radical path that would bring energy-related CO$_2$ emissions back to current levels by 2030, through more aggressive action on energy efficiency and transport and energy technologies, including the use of second generation biofuels and carbon capture and storage.

---

[51] The alternative policy scenario entails more investment in energy efficient infrastructure, but less investment in energy production and distribution. These effects broadly cancel one another out so investment requirements are about the same as in the reference case.

9.10 Conclusion

The technology-based analysis discussed in this chapter identifies one set of ways in which total GHG emissions could be reduced to three-quarters of current levels by 2050 (consistent with a 550ppm CO_2e stabilisation trajectory). The costs of doing so amount to under $1 trillion in 2050, which is relatively modest in relation to the level and expansion of economic output over the next 50 years, which in any scenario of economic success is likely to be over one hundred times this amount. They equate to around 1 ± 2½ % of annual GDP – with the IEA analysis suggesting that the costs could be close to zero. As discussed in the next chapter, this finding is broadly consistent with macroeconomic modelling exercises. Chapter 10 also looks at the possible cost implications of aiming for more restrictive stabilisation targets such as 450ppm CO_2e.

This resource-cost analysis suggests that a globally rational world should be able to tackle climate change at low cost. However, the more imperfect, less rational, and less global policy is, the more expensive it will be. This will also be examined further in the next chapter.

References

Relatively little work has been done looking cost effective emission savings possible from non-fossil fuel sources. The IPCC Working Group III Third Assessment Report (TAR, published in 2001) is the best source of non-fossil fuel emission savings, while work commissioned for the Stern Review by Grieg-Gran covers the latest analysis on tacking deforestation. The Stern Review has also commissioned a report on deforestation. IPCC has also produced estimates of fossil fuel related emission savings (2001). IPCC emission saving estimates are expected to be updated in the Fourth Assessment Report (to be published 2007). The International Energy Agency has produced a series of publications on how to cut fossil fuel emissions cost effectively; their most up to date estimates of aggregate sector-wide results are presented in the Energy Technology Perspectives (2006) and World Energy Outlook 2006 (in press). Dennis Anderson produced a simple analysis of how fossil fuel emissions can be reduced for the Stern Review, looking forward to 2075 (full paper published on Stern Review web site).

Ahmad, E. and N.H. Stern (1991): 'The theory and practice of tax reform in developing countries', Cambridge: Cambridge University Press.

Anderson, D. (2006) 'Costs and finance of carbon abatement in the energy sector'. Paper for the Stern Review ' available from www.sternreview.org.uk

Atkinson, A.B. and N.H. Stern (1974) 'Pigou, taxation and public goods', Review of Economic Studies, **41**(1): 119-128

Benitez, P.C., I. McCallum, M. Obersteiner and Y. Yamagata (2005): 'Global potential for carbon sequestration: Geographical distribution, country risk and policy implications'. Ecological Economics.

Dreze, J. and N.H. Stern (1987): 'The theory of cost-benefit analysis', in Chapter 14, A.J. Auerbach and M. Feldstein (eds.), Handbook of Public Economics volume 2.

Dreze, J. and N.H. Stern (1990): 'Policy reform, shadow prices, and market prices', Journal of Public Economics, Oxford: Elsevier, **42**(1): 1-45

EPA (forthcoming): ‘Global anthropogenic Non-CO_2 greenhouse-gas emissions: 1990-2020’, US Environmental Protection Agency, Washington DC. Figures quoted from draft December 2005 version.

Grieg-Gran, M. (2006): 'The Cost of Avoiding Deforestation', Report prepared for the Stern Review, International Institute for Environment and Development.

Hannah, L. (1979): 'Electricity before nationalisation: A study of the development of the electricity supply industry in Britain to 1948', Baltimore and London: The Johns Hopkins University Press.

International Energy Agency (2000): 'Experience curves for energy technology policy', Paris: OECD/IEA.

International Energy Agency (2005): 'World Energy Outlook 2005', Paris: OECD/IEA.

International Energy Agency (2006): 'Energy Technology Perspectives: Scenarios and Strategies to 2050' Paris: OECD/IEA.

International Energy Agency (in press): ‘World Energy Outlook 2006’ Paris: OECD.

Intergovernmental Panel on Climate Change (2000): 'Land-use, land-use change and forestry', Special Report of the Intergovernmental Panel on Climate Change [Watson RT, Noble IR, Bolin B et al. (eds.)], Cambridge: Cambridge University Press.

Intergovernmental Panel on Climate Change (2001): Climate Change 2001: 'Mitigation'. Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Metz B, Davidson O, Swart R and Pan J (eds.)], Cambridge: Cambridge University Press.

Intergovernmental Panel on Climate Change (2005): "'IPCC Special Report on Carbon Capture and Storage", Cambridge: Cambridge University Press, November, available from http://www.ipcc.ch/activity/ccsspm.pdf

Read, P. (2006): 'Carbon Cycle Management with Biotic Fixation and Long-term Sinks', in Avoiding Dangerous Climate Change, H.J. Schellnhuber et al. (eds.), Cambridge: Cambridge University Press, pp. 373 - 378.

Sachs, J. and K. Lackner (2005): 'A robust strategy for sustainable energy,' Brookings Papers on Economic Activity, Issue 2, Washington, D.C: The Brookings Institution.

Sathaye, J., W. Makundi, L. Dale and P. Chan (2005 in press): 'GHG mitigation potential, costs and benefits in global forests: a dynamic partial equilibrium approach'. Energy Journal.

Smith, P., D. Martino, Z. Cai, et al. (2006 in press): 'Greenhouse-gas mitigation in agriculture', Philosophical Transactions of the Royal Society, B.

Sohngen B and R. Mendelsohn (2003): 'An optimal control model of forest carbon sequestration', American Journal of Agricultural Economics **85** (2): 448-457, doi: 10.1111/1467-8276.00133

10 Macroeconomic Models of Costs

Key Messages

Broader behavioural modelling exercises suggest a wide range of costs of climate-change mitigation and abatement, mostly lying in the range –2 to +5% of annual GDP by 2050 for a variety of stabilisation paths. These capture a range of factors, including the shift away from carbon-intensive goods and services throughout economies as carbon prices rise, but differ widely in their assumptions about technologies and costs.

Overall, the expected annual cost of achieving emissions reductions, consistent with an emissions trajectory leading to stabilisation at around 500-550ppm CO_2e, is likely to be around 1% of GDP by 2050, with a range of +/- 3%, reflecting uncertainties over the scale of mitigation required, the pace of technological innovation and the degree of policy flexibility**.**

Costs are likely to rise significantly as mitigation efforts become more ambitious or sudden, suggesting that efforts to reduce emissions rapidly are likely to be very costly.

The models arriving at the higher cost estimates for a given stabilisation path make assumptions about technological progress that are pessimistic by historical standards and improbable given the cost reductions in low-emissions technologies likely to take place as their use is scaled up.

Flexibility over the sector, technology, location, timing and type of emissions reductions is important in keeping costs down. By focusing mainly on energy and mainly on CO_2, many of the model exercises overlook some low-cost abatement opportunities and are likely to over-estimate costs. Spreading the mitigation effort widely across sectors and countries will help to ensure that emissions are reduced where is it cheapest to do so, making policy cost-effective.

While cost estimates in these ranges are not trivial, they are also not high enough seriously to compromise the world's future standard of living – unlike climate change itself, which, if left unchecked, could pose much greater threats to growth (see Chapter 6). An annual cost rising to 1% of GDP by 2050 poses little threat to standards of living, given that economic output in the OECD countries is likely to rise in real terms by over 200% by then, and in developing regions as a whole by 400% or more.

How far costs are kept down will depend on the design and application of policy regimes in allowing for 'what', 'where' and 'when' flexibility in seeking low-cost approaches. Action will be required to bring forward low-GHG technologies, while giving the private sector a clear signal of the long-term policy environment (see Part IV).

Well-formulated policies with global reach and flexibility across sectors will allow strong economic growth to be sustained in both developed and developing countries, while making deep cuts in emissions.

10.1 Introduction

The previous chapter calculated the price impact of increasing fossil-fuel costs on the economy and then developed a detailed technology-based estimation approach, in which the costs of a full range of low GHG technologies were compared with fossil fuels for a path with strong carbon emissions abatement. A low-carbon economy with manageable costs is possible, but will require a portfolio of technologies to be developed. Overall, the economy-wide costs were found to be around 1% of GDP, though there remains a wide range reflecting uncertainty over future innovation rates and future fossil-fuel extraction costs and prices.

The focus of this chapter is a comparison of more detailed behavioural modelling exercises, drawing on a comparative analysis of international modelling studies. Different models have been tailored to tackle a range of different questions in estimating the total global costs of moving to a low-GHG economy. Section 10.2 highlights the results from these key models. The models impose a variety of assumptions, which are identified in section 10.3 and reflect uncertainty about the real world and differences of view about the appropriate model structure and, in turn, yield a range of costs estimates. The section investigates the degree to which specific model structures and characteristics affect cost estimates, in order to draw conclusions about which estimates are the most plausible and what factors in the real world are likely to influence them. Section 10.4 puts these estimated costs into a global perspective. There are also important questions about how these costs will be distributed, winners and losers, and the implications of countries moving at different speeds. These are examined further in Chapter 11.

The inter-model comparison reaffirms the conclusion that climate-change mitigation is technically and economically feasibl,e with mid-century costs most likely to be around 1% of GDP, +/- 3%.

Nevertheless, the full range of cost estimates in the broader studies is even wider. This reflects the greater number of uncertainties in the more detailed studies, not only over future costs and the treatment of innovation, but also over the behaviour of producers and consumers and the degree of policy flexibility across the globe. Any models that attempt to replicate consumer and producer behaviours over decades must be highly speculative. Particular aspects can drive particular results especially if they are ‘run forward’ into the distant future. Such are the difficulties of analysing issues that affect millions of people over long time horizons. However, such modelling exercises are essential, and the presence of such a broad and growing range of studies makes it possible to draw judgements on what are the key assumptions.

10.2 Costs of emissions-saving measures: results from other models

A broader assessment of mitigation costs requires a thorough modelling of consumer and producer behaviour, as well as the cost and choice of low-GHG technologies.

There have been a number of modelling exercises that attempt to determine equilibrium allocations of energy and non-energy emissions, costs and prices (including carbon prices), consistent with changing behaviour by firms and households. The cost estimates that emerge from these models depend on the assumptions that drive key relationships, such as the assumed ease with which consumers and producers can substitute into low-GHG activities, the degree of foresight in making investment decisions and the role of technology in the evolution of costs.

To estimate how costs can be kept as low as possible, models should cover a broad range of sectors and gases, as mitigation can take many forms, including land-use and industrial-process emissions.

Most models, however, are restricted to estimating the cost of altered fossil-fuel combustion applied mostly to carbon, as this reduces model complexity. Although fossil-fuel combustion accounts for more than three-quarters of developed economies’ carbon emissions, this simplifying assumption will tend to over-estimate costs, as many low-cost mitigation opportunities in other sectors are left out (for example, energy efficiency, non-CO_2 emissions mitigation in general, and reduced emissions from deforestation; see Chapter 9). Some of the most up-to-date and extensive comparisons surveyed in this section include:

- Stanford University's Energy Modelling Forum (EMF);
- the meta-analysis study by Fischer and Morgenstern (Resources For the Future (2005));
- the International Energy Agency accelerated technology scenarios;
- the IPCC survey of modelling results;
- the Innovation Modelling Comparison Project (IMCP)
- the Meta-Analysis of IMCP model projections by Barker et al (2006);
- the draft US CCSP Synthesis and Assessment of "Scenarios of Greenhouse-Gas Emissions and Atmospheric Concentrations and Review of Integrated Scenario Development and Application" (June 2006).

The wide range of model results reflects the design of the models and their choice of assumptions, which itself reflects the uncertainties and differing approaches inherent in projecting the future.

Figure 10.1 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. Although most of the model estimates for 2050 are clustered in the –2 to 5% of GDP loss in the final-year cost range, these costs depend on a range of assumptions. 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. A notable feature, examined in more detail below, is the greater-than-proportionate increase in costs to any rise in the amount of mitigation.

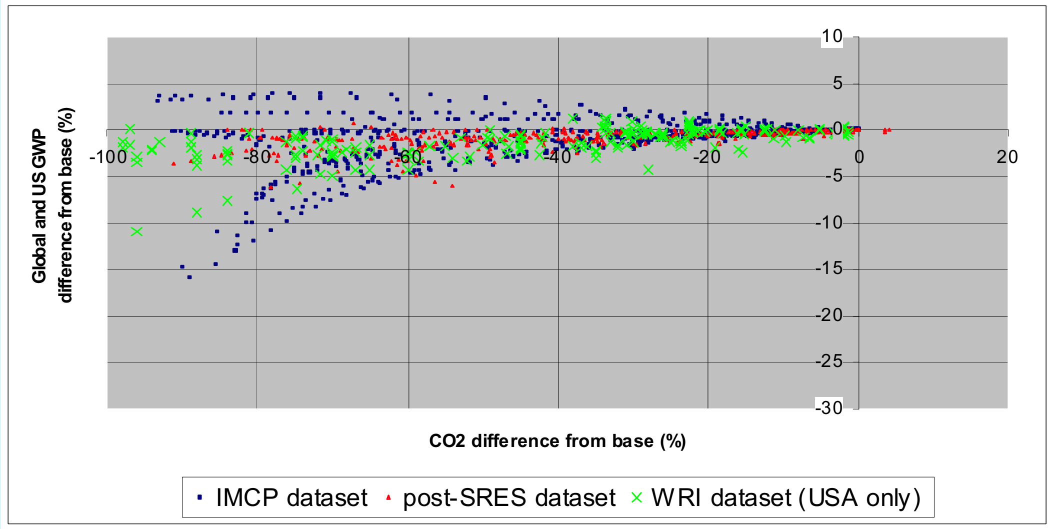
This variation in cost estimates is driven by a diversity of characteristics in individual models. To take two examples, the AIM model shows a marked rise in costs towards 2100, reflecting the use of only one option – energy conservation – being induced by climate policy, so that costs rise substantially as this option becomes exhausted. At the opposite extreme, the E3MG global econometric model assumes market failures due to increasing returns and unemployed resources in the base case. This means that additional energy-sector investment, and associated innovation driven by stabilisation constraints, act to *increase* world GDP. The fact that there is such a broad range of studies and assumptions is welcome, making it possible to use meta-analysis[1] to determine what factors drive the results.

---

[1] In statistics, a meta-analysis combines the results of several studies that tackle a set of related research hypotheses. In order to overcome the problem of reduced statistical power in individual studies with small sample sizes, analysing the results from a group of studies can allow more accurate data analysis.

Figure 10.1 Scatter plot of model cost projections

Costs of CO_2 reductions as a fraction of world GDP against level of reduction



Source: Barker et al. (2006)

Model comparison exercises help to identify the reasons why the results vary.

To make sense of the growing range of estimates generated, model comparison exercises have attempted to synthesise the main findings of these models. This has helped to make more transparent the differences between the assumptions in different models. A meta-analysis of leading model simulations, undertaken for the Stern Review by Terry Barker[2], shows that some of the higher cost estimates come from models with limited substitution opportunities, little technological learning, and limited flexibility about when and where to cut emissions[3].

The meta-analysis work essentially treats the output of each model as data, and then quantifies the importance of parameters and assumptions common to the various models in generating results. The analysis generates an overarching model, based on estimates of the impacts of individual model characteristics. This can be used to predict costs as a percentage of world GDP in any year, for any given mitigation strategy. Table 10.1 shows estimated costs in 2030 for stabilisation at 450ppm CO_2. This corresponds with approximately 500-550ppm CO_2e, assuming adjustments in the emissions of other gases such that, at stabilisation, 10-20% of total CO_2e will be composed of non-CO_2 gases (see Chapter 8).

A feature of the model is that it can effectively switch on or off the factors identified as being statistically and economically significant in cutting costs. For example, the 'worst case' assumption assumes that all the identified cost-cutting factors are switched off – in this case, costs total 3.4% of GDP. At the other extreme, the 'best case' projection assumes all the identified cost-cutting factors are active, in which case mitigation yields net benefits to the world economy to the tune of 3.9% of GDP. (Table 10.1 lists the individual estimated contributions to costs from the identified assumptions – a positive percentage point contribution represents the average reduction in costs when the parameter is 'switched on').

---

[2] Terry Barker is the Director of the Cambridge Centre for Climate Change Mitigation Research (4CMR), Department of Land Economy, University of Cambridge, Leader of the Tyndall Centre's research programme on Integrated Assessment Modelling and Chairman of Cambridge Econometrics. He is a Coordinating Lead Author in the IPCC's Fourth Assessment Report, due 2007, for the chapter covering mitigation from a cross-sectoral perspective.

[3] Barker et al. (2006) but see also Barker et al. (2004) and Barker (2006)

Table 10.1 Meta-analysis estimates

Average impact of model assumptions on world GDP in 2030 for stabilisation at 450ppm CO_2 (approximately 500-550ppm CO_2e)
(% point levels difference from base model run)

	Full equation
Worst case assumptions	**-3.4**
Active revenue recycling[4]	1.9
CGE model	1.5
Induced technology	1.3
Non-climate benefit	1.0
International mechanisms	0.7
'Backstop' technology	0.6
Climate benefit	0.2
Total extra assumptions	**7.3**
Best-case assumptions	**3.9**

Source: Barker et al. 2006

It is immediately obvious that no model includes all of these assumptions to the extent suggested here. This is because in practice, not all the cost-cutting factors are likely to apply to the extent indicated here, and the impact of each assumption is likely to be exaggerated (for example the active recycling parameter is based on the data from only one model[2]).

Nevertheless, the exercise suggests that the inclusion in individual models of induced technology, averted non-climate-change damages (such as air pollution) and international emission-trading mechanisms (such as carbon trading and CDM flows), can limit costs substantially.

The time paths of costs also depend crucially on assumptions contained within the modelling exercises. A number of models show costs rising as a proportion of output through to the end of the century, as the rising social cost of carbon requires ever more costly mitigation options to be utilised. Other models show a peak in costs around mid-century, after which point costs fall as a proportion of GDP, reflecting cost reductions resulting from increased innovation (see Section 10.3). In addition, greater disaggregation of regions, sectors and fuel types allow more opportunities for substitution and hence tend to lower the overall costs of GHG mitigation, as does the presence of a 'backstop' technology[5].

10.3 Key assumptions affecting cost estimates

Other model-comparison exercises, including studies broadening the scope to include non-carbon emissions, draw similar conclusions to the Barker study. A number of key factors emerge that have a strong influence in determining cost estimates. These explain not only the different estimates generated by the models, but also some of the uncertainties surrounding potential costs in the real world. These considerations are central, not only to generating realistic and plausible cost estimates, but also to formulating policies that might keep costs

---

[4] The parameter can be interpreted as switched 'off' for models where no account is taken of revenues (effectively only the changes in relative prices are modelled) and 'on' for models where the revenues are recycled in some way. Unfortunately, the data underpinning this parameter are thin: among the IMCP models, only E3MG models the use of revenues at all.

[5] Under the assumption of a 'backstop' technology, energy becomes elastic in supply and the price of energy is determined independently of the level of demand. Thus, 'backstop' technologies imply lower abatement costs with the introduction of carbon taxes. The 'backstop' price may vary through technical change. For example, wind, solar, tidal and geothermal resources may serve as 'backstop' technologies, whereas nuclear fission is generally not, because of its reliance on a potentially limited supply of uranium. In practice, very few technologies will be entirely elastic in supply: even wind farms may run out of sites, and the best spots for catching and transporting electricity from the sun may be exhausted quickly.

low for any given mitigation scenario. The overarching conclusion of the model studies is that costs can be moderated significantly if many options are pursued in parallel and new technologies are phased in gradually, and if policies designed to induce new technologies start sooner rather than later. The details will be quantified bellow, but the following key features are central to determining cost estimates.

Assumed baseline emissions determine the level of ambition.

The cost of stabilising GHG emissions depends on the amount of additional mitigation required. This is given by the 'mitigation gap' between the emissions goal and the 'business as usual' (BAU) emissions profile projected in the absence of climate-change policies. Scenarios with larger emissions in the BAU scenario will require greater reductions to reach specific targets, and will tend to be more costly. Large differences in baseline scenarios reflect genuine uncertainty about BAU trends, and different projected paths of global economic development.

The 2004 EMF study found a marked divergence in baseline Annex 1 (rich) country emissions projections from around 2040. Rich-country emissions begin at around 26$GtCO_2$ at the start of the century and then rise to a range of 40-50$GtCO_2$ by mid-century. By 2100, the range of BAU projections fans out dramatically. Some baseline scenarios show emissions dropping back towards levels at the start of the century while others show emissions rising towards 95 $GtCO_2$; there is an even spread between these extremes. These different paths encompass a variety of assumptions about energy efficiency, GHG intensity and output growth, as well as about exogenous technological progress and land-use policies.

Technological change will determine costs through time.

Costs vary substantially between studies, depending on the assumed rate of technological learning, the number of learning technologies included in the analysis and the time frame considered[6]. Many of the higher cost estimates tend to originate from models without a detailed specification of alternative technological options. The Barker study found that the inclusion of induced technical change could lower the estimated costs of stabilisation by one or two percentage points of GDP by 2030 (see table 10.1). All the main studies found that the availability of a non-GHG 'backstop' (see above) lowered predicted costs if the option came into play. Chapter 16 shows that climate policies are necessary to provide the incentive for low-GHG technologies. Without a 'loud, legal and long' carbon price signal, in addition to direct support for R&D, the technologies will not emerge with sufficient impact (see Part IV).

How far costs are kept down will depend on the design and application of policy regimes in allowing for 'what', 'where' and 'when' flexibility in seeking low-cost approaches. Action will be required to bring forward low-GHG technologies, while giving the private sector a clear signal of the long-term policy environment (see Part IV).

Abatement costs are lower when there is 'what' flexibility: flexibility over how emission savings are achieved, with a wide choice of sectors and technologies and the inclusion of non-CO_2 emissions.

Flexibility between sectors. It will be cheaper, per tonne of GHG, to cut emissions from some sectors rather than others because there will be a larger selection of better-developed technologies in some. For example, the range of emission-saving technologies in the power generation sector is currently better developed than in the transport sector. However, this does not mean that the sectors with a lack of technology options do nothing in the meantime. Indeed, innovation policies will be crucial in bringing forward clean technologies so that they are ready for introduction in the long term. The potential for cost-effective emission saving is also likely to be less in those sectors in which low-cost mitigation options have already been undertaken. Similarly, flexibility between demand sectors is also likely to reduce modelled costs. Models that are restricted to a narrow range of sectors with inelastic demand, for

---

[6] Grubb et al. (2006). See also Grubler et al. (1999), Nakićenović (2000), Jaffe et al. (2003) and Köhler (2006)

example, parts of the transport sector, will tend to estimate very high costs for a given amount of mitigation (see Section 10.2).

Flexibility between technologies. Using a portfolio of technologies is cheaper because individual technologies are prone to increasing marginal costs of abatement, making it cheaper to switch to an alternative technology or measure to secure further savings. There is also a lot of uncertainty about which technologies will turn out to be cheapest so it is best to keep a range of technology options open. It is impossible to predict accurately which technologies will experience breakthroughs that cause costs to fall and which will not.

Flexibility between gases. Broadening the scope of mitigation in the cost-modelling exercises to include non-CO_2 gases has the potential to lower the costs by opening up additional low-cost abatement opportunities. A model comparison by the Energy Modelling Forum[7] has shown that including non-carbon greenhouse gases (NCGGs) in mitigation analysis can achieve the same climate goal at considerably lower costs than a CO_2-only strategy. The study found that model estimates of costs to attain a given mitigation path fell by about 30–40% relative to a CO_2-only approach, with the largest benefits occurring in the first decades of the scenario period, with abatement costs on the margin falling by as much as 80%. It is notable that the impacts on costs are very substantial in comparison to the much smaller contribution of NCGGs to overall emissions, reflecting the low-cost mitigation options and the increase in flexibility of abatement options from incorporating a multi-gas approach[8] [9].

However, given that climate change is a product of the stock of greenhouse gases in the atmosphere, the lifetime of gases in the atmosphere also has to be taken into account (see Chapter 8). Strategies that focus too much on some of the shorter-lived gases risk locking in to high future stocks of the longer-lived gases, particularly CO_2.

Some countries can cut emissions more cheaply than other countries, so 'where' flexibility is important.

Flexibility over the distribution of emission-saving efforts across the globe will also help to lower abatement costs, because some countries have cheaper abatement options than others[10].

- **The natural resource endowments of some countries will make some forms of emissions abatement cheaper than in other countries**. For example, emission reduction from deforestation will only be possible where there are substantial deforestation emissions. Brazil is well suited to growing sugar, which can be used to produce biofuel cheaply, although, to the extent that biofuels can be transported, other countries are also likely to benefit. Brazil, like many other developing countries, also has a very good wind resource. In addition, the solar resources of developing countries are immense, the incident solar energy per m^2 being 2-2.5 times greater than in most of Europe, and it is better distributed throughout the year (see Chapter 9).

- **Countries that have already largely decarbonised their energy sector are likely to find further savings there expensive.** They will tend to focus on the scope for

---

[7] EMF-21; see Weyant et al. (2004), van Vuuren et al. (2006)

[8] The EMF found that as much as half of agriculture, waste and other non-CO_2 emissions could be cut at relatively low cost. The study looked at how the world might meet a stabilisation objective if it selected the least-cost abatement among energy-related CO_2 emissions and non-CO_2 emissions (but not land use). Two stabilisation scenarios were compared (aimed at stabilising emissions to 650ppm CO_2e): one in which only energy-related CO_2 emissions could be cut; and another in which energy-related CO_2 emissions and non-CO_2 gases could be reduced. In the 'energy-related CO_2 emissions only' scenario, CO_2 emissions fall by 75% on baseline levels in 2100. Some non-CO_2 gases also fall as an indirect consequence. In the multi-gas scenario, CO_2 emissions fall by a lesser extent (67% by 2100) and there are significant cuts in the non-CO_2 gases (CH4 falling by 52%, N_2O by 38%, F-gases by 73%). CO_2 remains the major contributor to emission savings, because it represents the biggest share in GHG emissions.

[9] Babiker et al. (2004)

[10] Discussion of which countries should pay for this abatement effort is a separate question. Part IV looks at how policy should be designed to achieve emissions reductions, while Chapter 11 examines the possible impacts on national competitiveness.

emissions cuts elsewhere. Energy-efficiency measures are typically among the cheapest abatement options, and energy efficiency varies hugely by country. For example, unit energy and carbon intensity are particularly low in Switzerland (1.2toe/$GDP and 59tc/$GDP respectively in 2002), reflecting the compositional structure of output and the use of low-carbon energy production. By contrast, Russia and Uzbekistan remain very energy- and carbon-intensive (12.5toe/$GDP and 840tc/$GDP respectively for Uzbekistan in 2002), partly reflecting aging capital stock and price subsidies in the energy market (see, for example, Box 12.3 on gas flaring in Russia).

- **It will also be cheaper to pursue emission cuts in countries that are in the process of making big capital investments.** The timing of emission savings will also differ by country, according to when capital stock is retired and when savings from longer-term investments such as innovation programmes come to fruition. Countries such as India and China are expected to increase their capital infrastructure substantially over coming decades, with China alone accounting for around 15% of total global energy investment. If they use low-emission technologies, emission savings can be 'locked in' for the lifetime of the asset. It is much cheaper to build a new piece of capital equipment using low-emission technology than to retro-fit dirty capital stock.

The Barker study also found that the presence of international mechanisms under the Kyoto Protocol (which include international emissions trading, joint implementation and the Clean Development Mechanism) allow for greater flexibility about where cuts are made across the globe. This has the potential to reduce costs of stabilising atmospheric GHG concentrations at approximately 500-550ppm CO_2e by almost a full percentage point of world GDP[11][12]. Similarly, Babiker et al. (2001) concluded that limits on 'where' flexibility, through the restriction of trading between sectors of the US economy, can substantially increase costs, by up to 80% by 2030.

Changes in consumer and producer behaviour through time are uncertain, so 'when' flexibility is desirable.

The timing of emission cuts can influence total abatement cost and the policy implications. It makes good economic sense to reduce emissions at the time at which it is cheapest to do so. Thus, to the extent that future abatement costs are expected to be lower, the total cost of abatement can be reduced by delaying emission cuts. However, as Chapter 8 set out, limits on the ability to cut emissions rapidly, due to the inertia in the global economy, mean that delays to action can imply very high costs later.

Also, as discussed above, the evolution of energy technologies to date strongly suggests that there is a relationship between policy effort on innovation and technology cost. Early policy action on mitigation can reduce the costs of emission-saving technologies (as discussed in Chapter 15).

Cost-effective planning and substituting activities across time require policy stability, as well as accurate information and well-functioning capital markets. Models that allow for perfect foresight together with endogenous investment possibilities tend to show much reduced costs. Perfect foresight is not an assertion to be taken literally, but it does show the importance of policy being transparent and predictable, so that people can plan ahead efficiently.

---

[11] Richels et al (1998) found that international co-operation through trade in emission rights is essential to reduce mitigation costs of the Kyoto protocol. The magnitude of the savings would depend on several factors including the number of participating countries and the shape of each country's marginal abatement cost curve. Weyant and Hill (1999) assessed the importance of emissions permits and found that they had the potential to reduce OECD costs by 0.1ppt to 0.9ppt by as early as 2010.

[12] For example, Reilly et al. (2004) compare the effectiveness of two GHG abatement regimes: a global regime of non-CO_2 gas abatement, and a regime that is globally less comprehensive and mimics the present ratification of the Kyoto Protocol. The study found that, by 2100, the abatement programme that is globally comprehensive, but has limited coverage of gases (non-CO_2 only), might be as much as twice as effective at limiting global mean temperature increases and less expensive than the Kyoto framework.

The ambition of policy has an impact on estimates of costs.

A common feature of the model projections was the presence of increasing marginal costs to mitigation. This applies not just to the total mitigation achieved, but also the speed at which it is brought about. This means that each additional unit reduction of GHG becomes more expensive as abatement increases in ambition and also in speed. Chapter 13 discusses findings from model comparisons and shows a non-linear acceleration of costs as more ambitious stabilisation paths are pursued. The relative absence of energy model results for stabilisation concentrations below 500ppm CO_2e is explained by the fact that carbon-energy models found very significant costs associated with moving below 450ppm, as the number of affordable mitigation options was quickly exhausted. Some models were unable to converge on a solution at such low stabilisation levels, reflecting the absence of mitigation options and inflexibilities in the diffusion of 'backstop' technologies.

In general, model comparisons find that the cost of stabilising emissions at 500-550pmm CO_2e would be around a third of doing so at 450-500ppm CO_2e.

The lesson here is to avoid doing too much, too fast, and to pace the flow of mitigation appropriately. For example great uncertainty remains as to the costs of very deep reductions. Digging down to emissions reductions of 60-80% or more relative to baseline will require progress in reducing emissions from industrial processes, aviation, and a number of areas where it is presently hard to envisage cost-effective approaches. Thus a great deal depends on assumptions about technological advance (see Chapters 9, 16 and 24). The IMCP studies of cost impacts to 2050 of aiming for around 500-550ppm CO_2e were below 1% of GDP for all but one model (IMACLIM), but they diverged afterwards. By 2100, some fell while others rose sharply, reflecting the greater uncertainty about the costs of seeking out successive new mitigation sources.

Consequently, the average expected cost is likely to remain around 1% of GDP from mid-century, but the range of uncertainty is likely to grow through time.

Potential co-benefits need to be considered.

The range of possible co-benefits is discussed in detail in Chapter 12. The Barker meta-analysis found that including co-benefits could reduce estimated mitigation costs by 1% of GDP. Such models estimate, for example, the monetary value of improved health due to reduced pollution and the offsetting of allocative efficiency losses through reductions in distortionary taxation. Pearce (1996) highlighted studies from the UK and Norway showing benefits of reduced air pollution that offset the costs of carbon dioxide abatement costs by between 30% and 100%. A more recent review of the literature[13] came to similar conclusions, noting that developing countries would tend to have higher ancillary benefits from GHG mitigation compared with developed countries, since, in general, they currently incur greater costs from air pollution.

Analyses carried out under the Clean Air for Europe programme suggest cost savings as high as 40% of GHG mitigation costs are possible from the co-ordination of climate and air pollution policies[14]. Mitigation through land-use reform has implications for social welfare (including enhanced food security and improved clean-water access), better environmental services (such as higher water quality and better soil retention), and greater economic welfare through the impact on output prices and production[15]. These factors are difficult to measure with accuracy, but are potentially important and are discussed further in Chapter 12.

---

[13] OECD et al. 2000

[14] Syri et al. 2001

[15] A difficulty in evaluating the exact benefits of climate polices to air pollution is the different spatial and temporal scales of the two issues being considered. GHGs are long-lived and hence global in their impact while air pollutants are shorter-lived and tend to be more regional or local in their impacts.

Box 10.1 The relationship between marginal and average carbon cost estimates

It is important to distinguish marginal from average carbon costs. In general, the marginal cost of carbon mitigation will rise as mitigation becomes more expensive, as low-cost options are exhausted and diminishing returns to scale are encountered. But the impact on overall costs to the economy is measured by the average cost of mitigation, which will be lower than those on the margin.

In some cases, for example, where energy efficiency increases or where induced technology reduces the costs of mitigation, average costs might not rise and could be zero or negative, even where costs on the margin are positive and rising. A survey for the US Congress by Lasky (2003) plotted carbon tax rates against losses in GDP. The correlation from the IMCP study is only 0.37; a similar low correlation from model results can be seen in Lasky's data on the US costs of Kyoto (2003, p.92).

Changes in the marginal carbon cost are related, but do not correspond one-for-one, to the average cost of mitigation. The social cost of carbon will tend to rise as the stock of atmospheric GHGs, and associated damages, rises. The marginal abatement cost will also rise, reflecting this, but average abatement costs may fall (see Chapter 9). This explains why some of the models with a high social cost of carbon, and corresponding high carbon price, show very low average costs. The high carbon price is assumed to be necessary to induce benefits from energy efficiency, technological innovation and other co-benefits such as lower pollution. In some cases, these result in a reduction in average costs that raise GDP above the baseline when a stabilisation goal is imposed. This also explains why the work by Anderson (Chapter 9) shows a falling average cost of carbon through time consistent with rising costs on the margin.

Most models represent incentives to change emissions trajectories in terms of the marginal carbon price required. This not only changes specific investments according to carbon content, but also triggers technical change through the various mechanisms considered in the models, including through various forms of knowledge investment. The IMCP project (Grubb et al. 2006) charts the evolution of carbon prices required to achieve stabilisation and shows that they span a wide range, both in absolute terms and in the time profile. For stabilisation at 450ppm (around 500-550ppm CO_2e), most models show carbon prices start off low and rise to US\$360/tCO_2 +/- 150% by 2030, and are in the range US\$180-900/tCO_2 by 2050, as the social cost of carbon increases and more expensive mitigation options need to be encouraged on the margin in order to meet an abatement goal.

After that, they diverge significantly: some increase sharply as the social cost of carbon continues to rise. Others level off as the carbon stock and corresponding social cost of carbon stabilise and a breadth of mitigation options and technologies serve to meet the stabilisation objective. Rising marginal carbon prices need not mean that GDP impacts grow proportionately, as new technologies and improved energy efficiency will reduce the economy's dependence on carbon, narrowing the economic base subject to the higher carbon taxation.

10.4 Understanding the scale of total global costs

Overall, the model simulations demonstrate that costs depend on the design and application of policy, the degree of global policy flexibility, and, whether or not governments send the right signals to markets and get the most efficient mix of investment. If mitigation policy is timed poorly, or if cheap global mitigation options are overlooked, the costs can be high.

To put these costs into perspective, the estimated effects of even ambitious climate change policies on economic output are estimated to be small – around 1% or less of national and world product, averaged across the next 50 to 100 years – provided policy instruments are applied efficiently and flexibly across a range of options around the globe. This will require early action to retard growth in the stock of GHGs, identify low-cost opportunities and prevent locking-in to high GHG infrastructure. The numbers involved in stabilising emissions are potentially large in absolute terms – maybe hundreds of billions of dollars annually (1% of current world GDP equates to approximately $350-400 billion) – but are small in relation to the level and growth of output.

For example, if mitigation costs 1% of world GDP by 2100, relative to the hypothetical 'no climate change' baseline, this is equivalent to the growth rate of annual GDP over the period dropping from 2.5% to 2.49%. GDP in 2100 would still be approximately 940% higher than today, as opposed to 950% higher if there were no climate-change to tackle. Alternatively, one can think of annual GDP being 1% lower through time, with the same growth rate, after an initial adjustment. The same level of output is reached around four or five months later than would be the case in the absence of mitigation costs[16].

The illustration of costs above assumes no change in the baseline growth rate relative to the various mitigation scenarios, that is, it takes no account of climate-change damages. In practice, by 2100, the impacts of climate change make it likely that the 'business as usual' level of world GDP will be lower than the post-mitigation profile (see Chapters 6 and 13). Hence stabilising at levels around 500-550ppm CO_2e need not cost more than a year's deferral of economic growth over the century with broad-based, sensible and comprehensive policies. Once damages are accounted for, mitigation clearly protects growth, while failing to mitigate does not.

The mitigation costs modelled in this chapter are unlikely to make the same kind of material difference to household lifestyles and global welfare as those which would arise with the probable impact of dangerous climate change, in the absence of mitigation (see section II). The importance of weighing together the costs, benefits and uncertainties through time is emphasised in Chapter 13.

10.5 Conclusion

This chapter draws on a range of model estimates with a variety of assumptions. A detailed analysis of the key drivers of costs suggests the estimated effects of ambitious policies to stabilise atmospheric GHGs on economic output can be kept small, rising to around 1% of national and world product averaged over the next fifty years.

By 2050, models suggest a plausible range of costs from –2% (net gains) to +5% of GDP, with this range growing towards the end of the century, because of the uncertainties about the required amount of mitigation, the pace of technological innovation and the efficiency with which policy is applied across the globe. Critically, these costs rise sharply as mitigation becomes more ambitious or sudden.

Whether or not the costs are actually minimised will depend on the design and application of policy regimes in allowing for 'what, where and when' flexibility, and taking action to bring forward low-GHG technologies while giving the private sector a clear signal of the long-term policy environment.

These costs, however, will not be evenly distributed. Issues around the likely distribution of costs are explored in the next chapter. Possible opportunities and benefits arising from climate-change policy also need to be taken into account in any serious consideration of what the true costs will be, and of the implications of moving at different speeds. These are examined further in Chapter 12.

---

[16] See, for example, Azar (2002)

References

Volume 2 of Jorgenson's book "Growth" and also Ricci (2003) provide a rigorous and thorough basis for understanding the theoretical framework against which to assess the costs of environmental regulation and GHG mitigation. The special edition of Energy Economics 2004 is also recommended and includes a crystal-clear introduction to modelling issues by John Weyant. The study by Fischer and Morgenstern (2005) also offers a comprehensive introduction to the key modelling issues, explaining divergent modelling results in terms of modelling assumptions, while highlighting the importance of 'what, where when' flexibility. Van Vuuren et al. (2006) are among those who take this a step further by allowing for multi-gas flexibility in modelling scenarios.

Edenhofer et al. (2006) review the results of ten IMCP energy modelling exercises examining the costs associated with different stabilisation paths, the dynamics of carbon prices and the importance of key assumptions, in particular, induced innovation. Barker et al. (2006) use a more a quantitative approach to synthesise the results of different model projections and examine the importance of induced technological innovation. Using a meta-analysis estimation technique, they attempt to quantify how important various modelling assumptions are in determining cost estimates for different mitigation scenarios.

Azar C. and S.H. Schneider (2002): 'Are the economic costs of stabilising the atmosphere prohibitive?' Ecological Economics **42**:(2002) 73–80

Babiker M.H., J. Reilly, J.M. Mayer, et al. (2001): 'The emissions prediction and policy analysis (EPPA) model: revisions, sensitivities and comparisons of results', Cambridge, MA: MIT Press.

Babiker M.H., J. Reilly, J.M. Mayer, et al. (2004): 'Modelling non-CO_2 Greenhouse-Gas Abatement', Netherlands Springer pp175-186, October.

Barker T., J. Köhler and M. Villena (2002): 'The costs of greenhouse-gas abatement: A Meta-Analysis of post-SRES mitigation scenarios.' Environmental Economics and Policy Studies **5**(2): 135-166

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.

Barker, T. (2004): 'Economic theory and the transition to sustainability: a comparison of general-equilibrium and space-time-economics approaches', Working Paper 62, November, Norwich: Tyndall Centre for Climate Change Research.

Edenhofer, O., K. Lessmann and M. Grubb (2005): 'Bringing down the costs of climate protection - Lessons from a modelling comparison exercise', Submission to Stern Review on the Economics of Climate Change, December.

Edenhofer, O., M. Grubb, K. C. Kemfert et al. (2006): 'Induced technological change: exploring its implications for the economics of atmospheric stabilization: Synthesis Report from the Innovation Modelling Comparison Project', The Energy Journal, Endogenous Technological Change and the Economics of Atmospheric Stabilisation Special Issue, April, 2006.

Fischer, C. and R.D. Morgenstern (2005): 'carbon abatement costs: why the wide range of estimates?' Resources for the Future, September, Discussion Paper 03–42 November.

Grubb, M., C. Carraro and J. Schellnhuber (2006): 'Technological change for atmospheric stabilisation: introductory overview to the Innovation Modelling Comparison Project' in The Energy Journal, Endogenous Technological Change and the Economics of Atmospheric Stabilisation Special Issue, April, 2006.

Grubb, M., J. Hourcade, O. Edenhofer and N. Nakicenovic (2005): 'Framing the Economics of Climate Change: an international perspective', Submission to the Stern Review on the Economics of Climate Change, December.

Grübler, A., N. Nakićenović and D.G. Viictor (1999): 'Modelling technological change: implications for the global environment', Annual Review Energy Environ **24**: 545–69

Jaffe AB, R.G. Newell and R.N. Stavins, (2003): 'Technological change and the environment' Handbook of Environmental Economics, Maler KG and Vincent JR Ed., **1**: 461-516

Jorgenson, D.W. and P.J. Wilcoxen (1990): 'Environmental regulation and U.S. economic growth' Rand Journal of Economics, **21**, No. 2, (Summer): 314-340

Jorgenson, D.W. (1998): 'Growth' Vol 2, Energy, the Environment, and Economic Growth. Cambridge, MA: MIT Press.

Köhler, J., M. Grubb, D. Popp and O. Edenhofer (2006): 'The transition to endogenous technical change in climate-economy models: a technical overview to the Innovation Modelling Comparison Project'. Energy Journal, **27**: 17-55

Lasky, M. (2003): 'The economic costs of reducing emissions of greenhouse gases: a survey of economic models'. CBO Technical Paper No. 2003-03 (May), Washington, DC: CBO.

Nakićenović, N. and A. Gritsevskyi. (2000): 'Modeling uncertainty of induced technological change', Laxenburg: International Institute for Applied Systems Analysis.

Organization for Economic Co-operation and Development, Resources for the Future, Intergovernmental Panel on Climate Change, and World Resources Institute, (2000): 'Ancillary benefits and costs of greenhouse-gas mitigation. Workshop on assessing the ancillary benefits and costs of greenhouse-gas mitigation strategies'. Washington DC, OECD.

Pearce, D.W., W.R. Cline, A. Achanta, et al. (1996): 'The social costs of climate change: greenhouse damage and the benefits of control', in Climate change 1995: economic and social dimensions of climate change, Cambridge: Cambridge University Press, pp. 183-224.

Reilly, J.M., M.C. Sarofim, S. Paltsev and R.G. Prinn (2004): 'The role of non- CO_2 greenhouse-gases in climate policy: analysis using the MIT IGSM', MIT Joint Program on the Science and Policy of Global Change, No. 114 (Aug) available from http://hdl.handle.net/1721.1/5543

Ricci, F. (2003): 'Channels of transmission of environmental policy to economic growth: a survey of the theory', Thema Universit´e de Cergy-Pontoise, July.

Richels, R.G. and A.S. Manne (1998): 'The Kyoto Protocol: A cost-effective strategy for meeting environmental objectives?' California: EPRI, Stanford University.

Sijm J.P.M. (2004): 'Induced technological change and spillovers in climate policy modeling: an assessment', ECN, December, Petten: ECN Beleidsstudies.

Syri, S., M. Amann, P. Capros, et al., (2001): Low- CO_2 energy pathways and regional air pollution in Europe. Energy Policy, **29**(11): 871-884

Weyant, J.P. and J. Hill (1999): 'The costs of the Kyoto protocol: a multi-model evaluation', Energy Journal, Introduction and Overview Pages vii-xliv.

Weyant, J.P. (ed.). (2004): 'EMF introduction and overview. Alternative technology strategies for climate change policy', Energy Economics Special Issue, **26**: 501-755

van Vuuren, D.P., J. Cofala, H.E. Eerens, et al. (2006): 'Exploring the ancillary benefits of the Kyoto Protocol for air pollution in Europe', Energy Policy, **34**: 444–460

van Vuuren, D.P., J.P. Weyant and F. de la Chesnaye (2006): 'Multi-gas scenarios to stabilize radiative forcing', Energy Economics, **28**(1): 102-120, January.

11 Structural Change and Competitiveness

Key Messages

The costs of mitigation will not be felt uniformly across countries and sectors. Greenhouse-gas-intensive sectors, and countries, will require the most structural adjustment, and the timing of action by different countries will affect the balance of costs and benefits.

If some countries move more quickly than others in implementing carbon reduction policies, there are concerns that carbon-intensive industries will locate in countries without such policies in place. A relatively small number of carbon-intensive industries could suffer significant impacts as an inevitable consequence of properly pricing the cost of greenhouse-gas (GHG) emissions.

The empirical evidence on trade and location decisions, however, suggests that only a small number of the worst affected sectors have internationally mobile plant and processes. Moreover, to the extent that these firms are open to competition this tends to come predominately from countries within regional trading blocs. This suggests that action at this regional level will contain the competitiveness impact.

Trade diversion and relocation are less likely, the stronger the expectation of eventual global action as firms take long-term decisions when investing in plant and equipment that will produce for decades.

International sectoral agreements for GHG-intensive industries could play an important role in promoting international action for keeping down competitiveness impacts for individual countries.

Even where industries are internationally mobile, environmental policies are only one determinant of plant and production location decisions. Other factors such as the quality of the capital stock and workforce, access to technologies, infrastructure and proximity to markets are usually more important determinants of industrial location and trade than pollution restrictions.

11.1 Introduction

All economies undergo continuous structural change through time. Indeed, the most successful economies are those that have the flexibility and dynamism to cope with and embrace change. Action to address climate change will require policies that deter greenhouse gas emitting activities, and stimulate a further phase of structural change.

One concern is that under different speeds of action, policies might be disproportionately costly to countries or companies that act faster, as they might lose energy-intensive production and exports to those who act more slowly. This could lead to relocation that simply transfers, rather than reduces, global emissions, making the costs borne by more active countries self-defeating.

Even where action is taken on a more uniform collective basis, concern remains that different countries will be affected differently. Some countries have developed comparative advantages in GHG-intensive sectors and would be hit hardest by attempts to rein-in emissions and shift activity away from such production.

The “competitiveness” of a firm or country is defined in terms of relative performance. An uncompetitive firm risks losing market share and going out of business. On the other hand, a country cannot “close”, but slow adjustment means the economy is likely to grow more slowly with lower real wage growth and enjoy fewer opportunities than more competitive economies. At the national level, promoting competitiveness means applying policies and re-vamping institutions to enable the economy to adapt more flexibly to new markets and opportunities, and facilitate the changes needed to raise productivity. Carefully designed, flexible policies to encourage GHG mitigation and stimulate innovation need not be inconsistent with enhancing national competitiveness. On the contrary, the innovation associated with tackling climate change could trigger a new wave of growth and creativity in the global economy. It is up to individuals, countries, governments and companies to tailor their policies and actions to seize the opportunities.

Section 11.2 looks at the likely distribution of carbon costs across industrial sectors and assesses their exposure to international competition. Section 11.3 examines evidence behind firms' location decisions and the degree to which environmental regulations influence trade patterns. Climate change policies may also help meet other goals, such as enhanced energy security, reduced local pollution and energy market reform and these issues are addressed in detail in the next chapter.

11.2 Distribution of costs and implications for competitiveness

To assess the likely impact of carbon costing, a disaggregated assessment of fuel inputs into various production processes is required. For many countries, this can be by analysing whole economy disaggregated Input-Output tables. Using the UK as a detailed case study, carbon costs can be applied to various fossil fuel inputs, and traced through the production process, to final goods prices. This reveals the carbon intensity of production. It also gives a crude estimate of the final impact on total consumer prices, and so reflects the reduction in consumer purchasing power[1].

The impacts of action to tackle climate change are unevenly distributed between sectors

Input-Output tables can be used to look at the distribution of carbon costs across sectors of the economy. For illustrative purposes, the UK, with energy intensity close to the OECD average, is used as a case study of disaggregated cost impacts. However, the lessons drawn for the UK need not be applicable to all countries, even within the OECD.

An illustrative carbon price of £70/tC ($30/tCO$_2$)[2] can be traced through the economy's disaggregated production process, to final consumer prices. Adding the carbon price raises the cost of fossil fuel energy in proportion to carbon intensity of each fossil fuel input (oil, gas and coal) see Box 11.1.

The overall impact is to raise consumer prices by just over one per cent on the assumption of a full cost pass-through. However, the impact on costs and prices in the most carbon-intensive industries, either directly or indirectly through their consumption of electricity, is considerably higher. In the UK, six industries out of 123 would face an increase in variable costs of 5% or more as a result of the impact of carbon pricing on higher energy costs (see table 11A.1 at end). In these industries prices would have to rise by the following amounts for profits to remain unchanged:

- gas supply and distribution (25%);
- refined petroleum (24%);
- electricity production and distribution (16%);
- cement (9%);
- fertilisers (5%);

---

[1] This assumes no behavioural response and no substitution opportunities and 100% pass through of costs. It is in theory possible to use older full supply-use Input-Output tables and the inverse Leontief matrix to gauge the rough magnitude of this higher order indirect impact. The study has not followed the impact through the entire supply-chain, but extending the analysis to include more multipliers shows the numbers converging to zero pretty quickly.

[2] This figure is illustrative, but the impact on prices is linear so the results can be appropriately factored up/down drawn for different carbon costs. Ideally this figure should correspond with the social cost of carbon (see Chapter 13), which to put it into context, is slightly above prices quoted in the European Emissions Trading scheme – ETS – over the much of the past year. It is important to distinguish tonnes of carbon from carbon dioxide as the two measures are used interchangeably. £1/tC = £0.273/tCO$_2$ so £70/tC = £19/tCO$_2$. Exchange rates are calculated at 2003 purchasing power parities.

- fishing (5%)

Although this analysis is restricted to the UK, it is these same industries, together with metals, chemicals, paper/pulp, and transport that dominate global carbon emissions from fossil fuels the world over. The competitiveness impacts in these sectors will be reduced to the extent that that they are not highly traded. In the UK, combined export and import intensity for these sectors is below 50% (See Box 11.3)[3].

Box 11.1 Potential costs to firms and consumers; UK Input-Output study

The primary users of fossil fuels (oil, gas and coal) as direct inputs include refined petrol, electricity, gas distribution, the fossil fuel extraction industries and fertiliser production. Figure A shows the share of oil & gas and coal in variable cost for these primary users.

Input-Output analysis can trace the impact of carbon pricing on secondary users of oil, gas and coal - defined as those industries that use inputs from the primary oil, gas and coal users such as electricity. Outputs from these sectors are then fed in as inputs to other sectors, and so on. For illustrative purposes, Figure B shows the impact of a carbon price of £70/tC, but the effects are linear with respect to price and so different impacts for different prices can be assessed using the appropriate multiple. Chapter 9 showed that although the average abatement cost may fall as new technologies arise, the marginal abatement cost is likely to rise with time, reflecting the rising social cost of carbon as the atmospheric carbon stock increases. As industry becomes decarbonised, the whole-economy impact is likely to begin to fall. But going the other way will be the rising social cost of carbon and the corresponding marginal abatement cost (this is illustrated in Box 9.6). This will have an increasing impact on costs in remaining carbon-intensive sectors.

Figure A Share of oil & gas and coal extraction in variable costs, percent

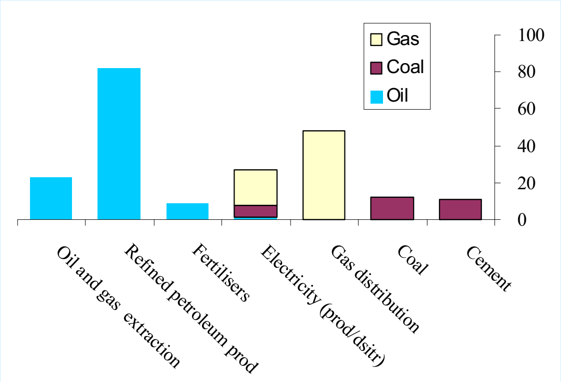
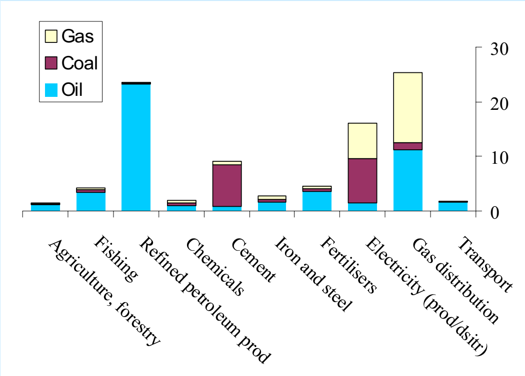


Figure B Product price increases from £70/tC pricing (full pass-through), percent



The largest users of petroleum-products include agriculture, forestry and fishing, chemicals and the transportation sectors. The main users of coal are electricity and cement. The main users of electricity include the electricity sector itself, a number of manufacturing industries and the utilities supplying gas and water.

Total fossil fuel energy costs account for 3% of variable costs in UK production. When the illustrative carbon price of £70/tC ($\$30/tCO_2$) is applied, whole economy production costs might be expected to rise by just over 1%. Only 19 out of 123 sectors, accounting for less than 5% of total UK output, would see variable costs increase of more than 2% and only six would undergo an increase of 5% or more[4].

---

[3] Trade intensity defined as total and exports of goods and services as a percentage of total supply of goods and services, plus imports of goods and services as a percentage of total demand for goods and services. Output is defined as gross, so the maximum value attainable is 200.

[4] Full industry listings for all 123 Standard Industrial Classification (SIC) sectors are given in annex table 11A.1.

Mapping costs through to final consumer goods prices, the aggregate impact on consumer prices of a £70/tC would be of the order of a 1.0% one-off increase in costs, with oil's contribution accounting for just under half and the remainder split between gas and coal[5].

Electricity and gas distribution for example are almost entirely domestic, and to the extent energy intensive industries do trade, this is mostly within the EU (trade intensity falls by a factor of two to seven for the key energy-intensive industries when measured in terms of non-EU trade only - see Annex table 11A.1 for details of trade intensity among carbon-intensive activities). Nevertheless:

- The magnitude of the impact on a small number of sectors is such that it could provide incentives for import substitution and incentives to relocate to countries with more relaxed mitigation regimes, even though these sectors are not currently characterised by high trade intensity. Further, many industries suffering smaller price increases are more open to trade, such as oil and gas extraction or air transport. The competitiveness impacts will be reduced if climate change action is coordinated globally.

- It is likely that some sectors (for example steel and cement or even electricity for a more inter-connected country) may be more vulnerable in countries bordering more relaxed mitigation regimes. Such countries should conduct similar Input-Output exercises to assess the vulnerability of their tradable sectors.

- In addition, there is a problem of aggregation. Aluminium smelting for example is among the most heavily energy-intensive industrial processes. Yet the upstream process is classed under 'non-ferrous metals' (of which aluminium accounts for around half). Hence although it is correct to conclude that overall value-added is not at much as risk, to infer that aluminium production is not at risk would be wrong. In general, upstream metal production tends to be both the most energy-intensive and tradable component, something that analysis at this level of aggregation may not reveal.

The forgoing analysis offers an indication of the distribution of static costs among various sectors from pricing-in the cost of GHG emissions. However, there is a risk that action to reduce GHG emissions could generate dynamic costs, for example, from scrapping capital prematurely and retraining workers. Before assessing these costs, it is important to re-emphasise that under 'business as usual' policies, dynamic costs relating to early capital scrapping and adjustment are liable to be even larger in the medium term. Timely investment will reduce the impact of climate change. Chapter 8 showed that a smooth transition to a low GHG environment with early action to reduce emissions is likely to limit adjustment costs.

The dynamic impacts from a transition to a low-GHG economy should be small. The change in relative prices that is likely to result from adopting the social cost of carbon into production activities is well within the 'normal' range of variation in prices experienced in an open economy. Input cost variations from recent fluctuations in the exchange rate and the world oil price, for example, are likely to far exceed the short-run primary energy cost increases from a carbon tax required to reflect the damage from emissions (see Box 11.2).

---

[5] It is in theory possible to use older full supply-use Input-Output tables and the inverse Leontief matrix to gauge the rough magnitude of this higher order indirect impact. Because data disaggregated to a level commodity output per unit of domestically met final demand has not been published in the UK since 1993, the study has not adopted this approach and has not been able to follow the impact through the entire supply-chain. However, extending the analysis to include more multipliers seems to make little difference to the results, suggesting the numbers presented here are a close approximation to the price impacts that would be derived using an up-to-date inverse Leontief.

Box 11.2 Vulnerability to energy shocks: lessons from oil and gas prices

Past energy price movements can be used to illustrate the likely economic impact of carbon pricing. Energy costs constitute a small part of total gross output costs, in most developed economies under 5%, in contrast to, say, labour costs, which account for up to a third of total gross output costs. Nevertheless, past movements in energy costs can offer a guide to the potential impact of carbon proving.

UK I-O tables show that oil and gas together account for more than ninety percent of the final value UK fossil fuel energy consumption, but only three-quarters of fossil fuel emissions, as coal is more carbon-intensive. The I-O data reveal that a £10/tC ($4/tCO$_2$) carbon price would have a similar impact on producer prices as a $1.6/bl rise in oil prices *with a proportionate gas price increase*.

To put this in context, the sterling oil price has risen 240% in real terms from its level over most of the period 1986-1997($18/bl) to around $69/bl (as of May 2006), and by 150% in real terms since 2003 (average), when the price of Brent crude hovered at around $26 a barrel for most of the year. On this basis, the change in the real oil price since 2003, assuming a proportionate changes in gas prices, is likely to have had a similar impact on the economy as unchanged oil and gas prices and the imposition of a £260/tC ($132/tCO$_2$) carbon price[6]. Or, alternatively, a £70/tC ($30/tCO$_2$) carbon resource cost is likely to have a similar impact as a $11/bl real oil price increase (at 2003 prices), according to I-O tables.

Gross estimate of impact on UK consumer prices and GDP*

Brent spot price $ per barrel (real)	Equivalent Carbon cost		Consumer prices, % change	GDP % change (prod'r prices)
	£/T carbon	$/T CO2		
2003 average, 26.3	0	0	0.0	0.0
38	**70**	30	0.9	**-1.2**
40	84	37	1.1	-1.5
60	206	90	2.6	-3.6
80	329	143	4.2	-5.7
100	451	196	5.8	-7.9

*Uses 2003 prices and Input-output tables; assumes no substitution in producer processes or consumption and all revenues are lost to economy.
Source: Stern using 2003 UK Input-Output tables, Carbon Trust carbon intensity and UK DTI energy price statistics.

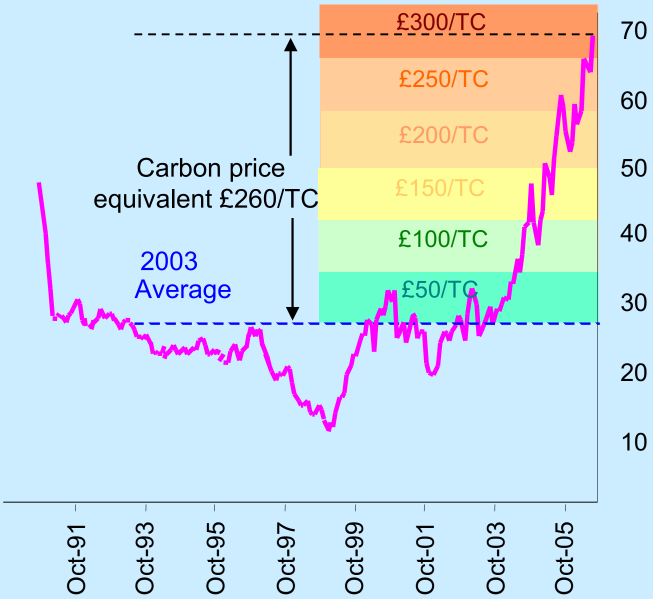
In practice, the overall impact on GDP from oil and gas price rises is likely to have been far smaller than suggested here at the national and global level. This is because the rise in the oil price in part reflects a transfer of rent to low marginal cost oil exporters, who in turn will spend more on imported goods and services from oil-importers. The presence of rent in the oil price means the impact on GDP is likely to be over-estimated even for oil importers. Furthermore, to the extent that carbon taxes generate transfers within the economy, the impact on GDP will also be exaggerated. Finally, the use of fixed input output tables assume consumer and producer behaviour is static (see Annex 9A for a comparison with other cost estimates).

In practice, costs will be lowered as firms and consumers switch out of more expensive carbon-intensive activities. Consequently, the total impact of both carbon costing and oil price changes on GDP will be lower than the numbers presented here, which should be regarded as an illustrative upper-end estimate of the costs of mitigation in the energy sector for applying any given carbon price.

---

[6] The exercise assumes that gas prices change in full proportion with oil prices, but that coal prices remain unchanged. In reality oil and gas prices tend to co-move as they are partial substitutes within a fossil fuel energy market and are linked contractually.

The recent rise in the Brent spot price, US $ per barrel (2003 prices)



Source: Ecowin, Stern

The economic literature investigating the impact of energy cost changes focuses disproportionately on resource, capital and energy-intensive sectors and firms. While this is understandable from a policy perspective, since regulation is likely to disproportionately affect these sectors, it also indicates a significant gap in data on other sectors in particular services, which constitute up to three quarters of some developed economies output.

The analysis also assumes that carbon costs are fully passed through to final prices. In practice this need not be the case, especially for tradable sectors that face sensitive demand and are likely to "price-to-markets" to avoid a loss of market share. In addition, the presence of competing inputs, and the opportunity to change processes and reduce emissions, also serve to limit the impact on both profits and prices. However, this analysis still gives an indication of which sectors are most vulnerable to a profit squeeze if carbon pricing is applied to emissions.

The nature of the policy instrument and the framework under which it is applied will also lead to sectoral distributions of costs. For example:

- Who bears the costs/gains from emissions trading depends on whether the allowances are auctioned or given out for free.

- The scope of trading schemes also matters. The EU ETS, for example, extends to primary carbon-intensive sectors, but does not allocate permits to secondary users, such as the aluminium sector, which relies heavily on electricity inputs[7].

- The structure of the electricity market also helps determine outcomes. In highly regulated or nationalised electricity markets, for example, carbon costs are not necessarily passed through, in which case the impact would be felt through the public finances. With regulation limiting cost pass-through in a private sector industry, there will be a squeeze on profits with impacts felt by shareholders. Different impacts will be felt across the globe, but the analysis here gives an indication of the sectors likely to be directly affected.

---

[7] For analysis of the structure and impact of the EU ETS see: Frontier Economics (2006); Carbon Trust (2004); Grubb (2004); Neuhoff (2006); Sijm et al. (2005) OXERA (2004) and Reinaud (2004).

International sectoral agreements for such industries could play an important role in both promoting international action and keeping down competitiveness impacts for individual countries. Chapter 22 shows how emissions intensities within sectors often vary greatly across the world, so a focus on transferring and deploying technology through sectoral approaches could reduce intensities relatively quickly. Global coverage of particular sectors that are internationally exposed to competition and produce relatively homogenous products can reduce the impact of mitigation policy on competitiveness. A sectoral approach may also make it easier to fund the gap between technologies in developed and developing countries.

Countries most reliant on energy-intensive goods and services may be hardest hit

The question of the distribution of additional costs applies to countries also. Some small agricultural or commodity-based economies rely heavily on long-distance transport to deliver products to markets while some newly-industrialising countries are particularly energy-intensive. Primary energy consumption as a percent of GDP is generally three or four times higher in the developing world than in the OECD[8], though in rapidly growing sectors and countries such as China and India, primary energy consumption per unit output has fallen sharply as new efficient infrastructure is installed (see Section 7.3). Some of these countries may benefit from energy efficiency improvements and energy market reforms that could lower real costs, but the distribution of costs raises issues relating to design of policies and different speeds of action required to help with the transition in certain countries and sectors (see Part VI).

The impact on oil and fossil fuel producers will depend on the future energy market and the rate of economic diversification in the relevant economies during the transition, which will open up new opportunities for exploiting and exporting renewable energy and new technologies such as carbon capture and storage. Producers of less carbon-intensive fossil fuels, such as gas, will tend to benefit relative to coal or lignite producers.

Where transfers are involved, the extra burden on rich countries need not be significant given the disparities in global income. For illustration, assume GHG stabilisation requires a commitment of 1% of world GDP annually to tackle climate change. If, in the initial decades, the richest 20% of the world's population, which produce 80% of the world's output and income, agreed to pay 20% more - or 1.2% of GDP, this would allow the poorer 80% of the worlds population to shoulder costs equivalent to only 0.2% of GDP[9]. Similarly, transfers to compensate countries facing disproportionately large and costly adjustments to the structure of their economies could also be borne at relatively small cost, if distributed evenly at a global level. Questions of how the costs of mitigation should be borne internationally are discussed in Part VI of this report.

11.3 Carbon mitigation policies and industrial location

The impact on industrial location if countries move at different speeds is likely to be limited

The transitional costs associated with implementing GHG reduction policies faster in one country than in another were outlined in the previous section. In the long run, however, when by definition, resources are fully employed and the impact for any single country is limited to the relocation of production and employment between industries, openness to trade allows for cheap imports to substitute domestic production in polluting sectors subject to GHG pricing. This is likely to reduce the long-run costs of GHG mitigation to consumers, while some domestic GHG-intensive firms that are relatively open to trade lose market share.

---

[8] International Energy Agency (2005).

[9] OECD economies account for 15% of the world's population and just over 75% of world output in terms of GDP at current prices using World Bank Statistics (2004). Use of market prices overstates the real value of output in rich countries relative to poorer countries because equivalent non-tradable output in general tends to be cheaper in poorer countries. However, in terms of ability to transfer income globally at market exchange rates, market prices are the appropriate measure.

A reduction in GHG-intensive activities is the ultimate goal of policies designed to reduce emissions. However, this aim is most efficiently achieved in an environment of global collective action (see Part VI). The is because if some countries move faster than others, the possible relocation of firms to areas with weaker GHG policies could reduce output in countries implementing active climate change policies by more than the desired amount (that is, the amount that would prevail in the case where *all* countries adopted efficient GHG policies). At the same time, global emissions would fall by less than the desired amount if polluters simply re-locate to jurisdictions with less active climate change policies[10].

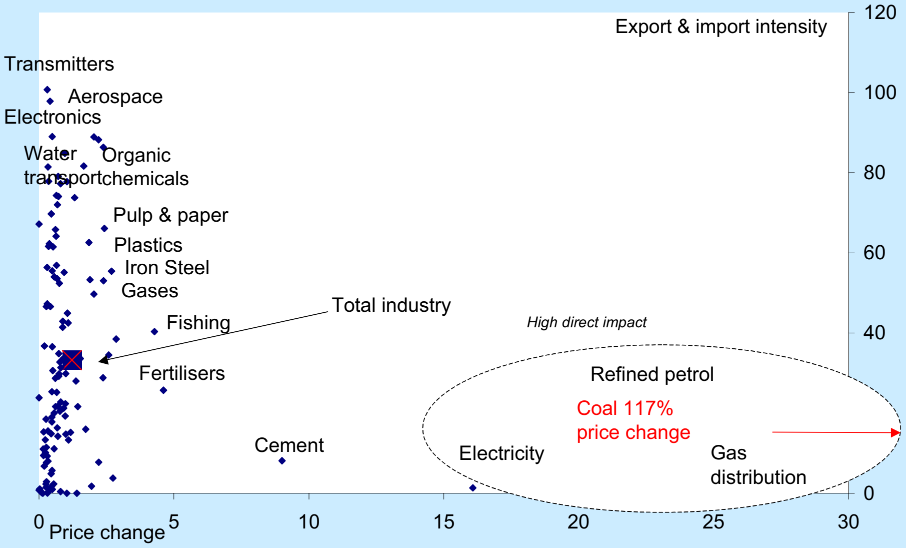
This risk should not be exaggerated. To the extent that energy-intensive industry is open to trade, the bulk of this tends to be limited to within regional trading blocks. UK Input-Output tables, for example, suggest trade diversion is likely to be reduced where action is taken at an EU level (see Box 11.3). However, several sectors are open to trade outside the EU. To the extent that variations in the climate change policy regime between countries result in trade diversion in these sectors the impact on GHG emissions will be reduced.

Box 11.3 The risk of trade diversion and firm relocation – a UK case-study

By changing relative prices, GHG abatement will reduce demand for GHG-intensive products. Sectors open to competition from countries not enforcing abatement policies will not be able to pass on costs to consumers without risking market share. The short-run response to such elastic demand is likely to be lower profits. In the long run, with capital being mobile, firms are likely to make location decisions on the basis of changing comparative advantages.

I-O analysis helps identify which industries are likely to suffer trade diversion and consider relocation: in general the list is short. Continuing with the £70/tC ($30/tCO$_2$) carbon price example, the figure below maps likely output price changes against exposure to foreign trade[11]. With the exception of refined petrol and coal, fuel costs are not particularly exposed to foreign trade. The price of electricity and gas distribution is set to rise by more than 15%, but output is destined almost exclusively for domestic markets. In all other cases, price increases are limited to below - mostly well below - 10%.

Vulnerable industries: price sensitivity and trade exposure, percent



The bulk of the economy is not vulnerable to foreign competition as a result of energy price rises. However, a few sectors are. Apart from refined petrol, these include fishing, coal, paper

---

[10] The ‘desired amount’ refers to the amount consistent with relative comparative advantages in a world with collective action, in a conceptual world where gains form trade are maximised.

[11] This is defined as exports of goods and services as a percentage of total supply of goods and services, plus imports of goods and services as a percentage of total demand for goods and services. Output is defined as gross, so the maximum value attainable is 200.

and pulp, iron and steel, fertilisers, air and water transport, chemicals, plastics, fibres and non-ferrous metals, of which aluminium accounts for approximately half of value added. In addition, the level of aggregation used in I-O analysis masks the likelihood that certain processes and facilities within sectors will be both highly energy-intensive and exposed to global competition.

The impact on competitiveness will depend not only on the strength of international competition in the markets concerned, but also the geographical origin of that competition. Many of the proposed carbon abatement measures (such as the EU ETS) are likely to take place at an EU level and energy-intensive sectors tend to trade very little outside the EU.

Trade intensity falls seven-fold in the cement industry when restricted to non-EU countries, as cement is bulky and hard to transport over long distances. Trade in fresh agricultural produce drops by a factor of 5 when restricted only to non-EU countries. The next largest drop in trade occurs in pulp and paper, plastics and fibres. Here trade intensity is quartered at the non-EU level. Trade intensity in plastics and iron and steel and land-transport as well as fishing and fertilisers drop by two-thirds. Trade intensity for air transport and refinery products halves in line with the average for all sectors (complete non-EU trade intensities are listed in Annex table 11A.1). All of these sectors are fossil fuel-intensive; suggesting that restrictions applied at the EU level would greatly diminish the competitiveness impact of carbon restrictions.

Trade diversion and relocation are also less likely, the stronger the expectation of eventual global action. Firms need to take long-term decisions when investing in plant and equipment intended for decades of production. One illustration of this effect is the growing aluminium sector in Iceland. Iceland has attracted aluminium producers from Europe and the US partly because a far greater reliance on renewable electricity generation has reduced its exposure to prices increases, as a result of the move to GHG regulations (see Box 11.4).

Box 11.4 Aluminium production in Iceland

Over the last six years, Iceland has become the largest producer of primary aluminium in the world on a per capita basis. The growth in aluminium production is the result both of expansion of an existing smelter originally built in 1969 and construction of a new green-field smelter owned by an American concern and operated since 1998. The near-future looks set to see a continuing sharp increase in aluminium production in Iceland. Both existing plants have plans for large expansions in the near future. These projects are forecast to boost aluminium production in Iceland to about one million tonnes a year, making Iceland the largest aluminium producer in western Europe.

Power-intensive operations like aluminium smelters are run by large and relatively footloose international companies. Iceland has access to both the European and US aluminium market, but its main advantage is the availability of water and emission-free, renewable energy. Emissions of CO_2 from electricity production per capita in Iceland is the lowest in the OECD: 70% of its primary energy consumption is met by domestic, sustainable energy resources. Iceland is also taking action to reduce emissions of fluorinated compounds associated with aluminium smelting. Expectations of future globalisation action to mitigate GHG emissions is already acting as a key driver in attracting investment of energy-intensive sectors away from high GHG energy suppliers and towards countries with renewable energy sources.

The impact on location and trade is likely to be more substantial for mitigating countries bordering large trade-partners with more relaxed regimes, such as Canada which borders the US, and Spain which is close to North Africa. For example, Canada's most important trading partner, the United States, has not signed the Kyoto Protocol, raising concerns of a negative competitive impact on Canada's energy-intensive industry.[12] However, even for open markets such as Canada and the US, or states within the EU, firms tend to be reluctant to relocate or

---

[12] For an interesting discussions see the Canadian Government's *Industry Canada* (2002) report, as well as in the representations of the Canadian Plastic Industry Association.

trade across borders, when they have markets in the home nation. This so-called “home-bias” effect is surprisingly powerful and the consequent necessity for firms to locate within borders to access local markets limits the degree to which they are footloose in their location decisions[13].

Theory suggests that country-specific factors, such as the size and quality of the capital stock and workforce, access to technologies and infrastructure, proximity to large consumer markets and trading partners, and other factor endowments are likely to be the most important determinants of location and trade. In addition, the business tax and regulatory environment, agglomeration economies, employment law and sunk capital costs are also key determinants. These factors are unlikely to be much affected by GHG mitigation policies. Overall, empirical evidence supports the theory, and suggests environmental policies do affect pollution-intensive trade and production on the margin, but there is little evidence of major relocations[14] [15].

Environmental policies are only one determinant of plant and production location decisions. Costs imposed by tighter pollution regulation are not a major determinant of trade and location patterns, even for those sectors most likely to be affected by such regulation.

The bulk of the world’s polluting industries remain located in OECD countries despite their tighter emissions standards[16] [17]. By the same token, 2003 UK Input-Output tables show that around 75% of UK trade in the output of carbon-intensive industries is with EU countries with broadly similar environmental standards, with little tendency for such products to be imported from less stringent environmental jurisdictions.

One way of assessing the impact of environmental regulations is to see if greater trade openness has led to a relocation of polluting industries to poorer countries, which have not tightened environmental standards. Antweiler, Copeland and Taylor (2001) calculated country-specific elasticities of pollution concentrations with respect to an increase in openness over the latter part of the twentieth century (Figure 11.1). A positive value for a country implies that trade liberalisation shifts pollution-intensive production towards that country, in effect signalling that it has a comparative advantage in such production.

---

[13] This was the finding of McCallum’s seminal 1995 paper, further reinforced by subsequent discussions such as Helliwell’s assessment of Canadian-US economic relations, and Berger and Nitsch’s (2005) gravity model of intra-EU trade, both of which found significant evidence of home-bias where borders inhibit trade despite short distances.

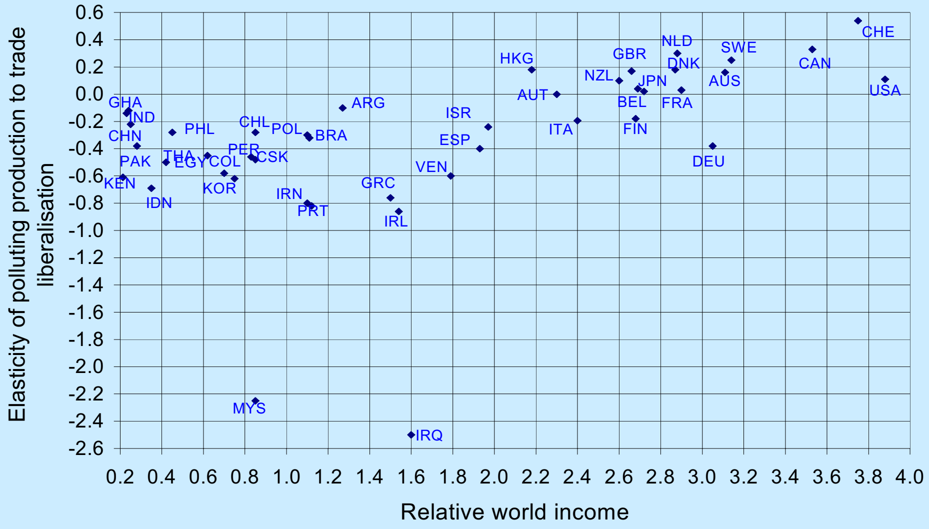
[14] See Copeland and Taylor (2004) for one of the most thorough-going theoretical and empirical investigation into environmental regulations and location decisions. See also Levinson et al (2003), Smita et al. (2004) Greenstone (2002), Cole et al. (2003), Ederington et al (2000, 2003), Jeppesen (2002), Xing et al. (2002), UNDP (2005).

[15] The analysis by Smita et al. (2004) confirms that other factors are likely to be more significant determinants of international location and direct investment decisions - factors such as the availability of infrastructure, agglomeration economies and access to large consumer markets. The study of the influence of air pollution regulations carried out by AEA Metroeconomica found that “it is extremely difficult to assess the impact of air pollutions on relocation from the other factors that determine location decisions.”

[16] Low and Yeats (1992) reported that over 90% of all 'dirty-good' production in 1988 was in OECD countries

[17] This fact alone suggests the location of dirty-good production across the globe reflects much more than weak environmental regulations. See also Trefler (1993) and Mani et al (1997).

Figure 11.1 Trade liberalisation reveals 'comparative advantages' in pollution



Source: Anweiler etal.

Perhaps surprisingly, the study found that rich countries have tended to have unexploited comparative advantages in pollution-intensive production and tend to have positive values for the elasticity while poorer countries tend to have negative values. This indicates that opening up trade will on average shift polluting production towards richer countries. The authors offer this as support for the view that factor endowments such as capital intensity, availability of technology and skilled labour, and access to markets and technologies are the key determinants of environmentally sensitive firms' location decisions. Such factors outweigh rich countries' tendency to apply tighter environmental restrictions in determining firms' location decisions.

11.4 Conclusion

The competitiveness threat arising if some countries move quicker than others in mitigating GHGs is, for most countries, not a macro-economic one, but certain processes and facilities could be exposed in the transition to a low-emissions environment, with new plant diverted to countries or regions with less active climate change policies.

However, if action is taken regionally, such impacts are likely to apply to only a very narrow subset of production in a few states with little impact on the economy as a whole. There is likely to be a differentiation in a country's attractiveness as an investment location towards less carbon-intensive activities, but with well-designed policies and flexible institutions there will also be new opportunities in innovative sectors.

Environmental policies are only one determinant of plant and production location decisions. Even for those sectors most likely to be affected by such regulation, factors such as the quality of the capital stock and workforce, access to technologies and infrastructure and the efficiency of the tax and regulation system are more significant. Proximity to markets and suppliers is another important determinant of location and trade. These fundamental factors will always be the key drivers of overall national competitiveness and dynamic economic performance.

Focusing on the costs of mitigation is not the whole story: there are a number of non-climate change related benefits that countries which take action to mitigate GHGs will benefit from; these are outlined in the next chapter.

References

General discussions defining competitiveness are few and far between, reflecting the fact that the definition varies depending on the context. An entertaining account of the problems associated with defining "competitiveness" and the limitations to the notion applied at a national level can be found in Krugman (1994) and at a more applied level in Azar (2005). There are a number of very thorough and well-researched sectoral analyses of the competitiveness impact of climate change policies; particularly informative are Demailly and Quirion (2006) study of competitiveness in the European cement industry and Berman and Bui's account of location decisions in the fossil fuel price sensitive refinery sector. There are also a host of in-depth studies of specific regional policies in particular the competitiveness impact of the EU ETS. Among the many notable reports listed below are: Frontier Economics (2006); Oxera (2006); Grubb Neuhoff (2006), and Reinaud (2004).

Perhaps the most authoritative and comprehensive account of the evolving literature on firms' location decisions in the presence of differential national environmental policies can be found in Copeland and Taylor (2004). Smita et al. (2004) and Lowe and Yeats also undertake in-depth analyses of the degree to which environmental regulations influence trade patters. McCallum (1995) and Nitsch and Berger (2005) provide illustrations of the impact of country borders in containing trade, even where borders are open and goods are highly tradable.

Antweiler, W., B.R. Copeland and M.S. Taylor, (2001): 'Is free trade good for the environment?' American Economic Review **91**(4): 877–908

Azar, C. (2005): 'Post-Kyoto climate policy targets: costs and competitiveness implications', Climate Policy journal 309-328

Berman, E. and L. Bui (1999): 'Environmental regulation and productivity: evidence from oil refineries' Review of Economics and Statistics 2001 **83**(3): 498-510, available from http://www.mitpressjournals.org/doi/abs/10.1162/00346530152480144

Brunnermeier, S.B. and Cohen M. (2003): 'Determinants of environmental innovation in U.S. manufacturing industries', Journal of Environmental Economics & Management, **45**(2): 278-293

Burtraw, D. (1996) "Trading emissions to clean the air: exchanges few but savings many," *Resources*, **122** (Winter): 3-6

The Carbon Trust (2004): 'The European Emissions Trading Scheme: implications for industrial competitiveness', London: The Carbon Trust.

The Carbon Trust (2005): 'The UK climate change programme: potential evolution of business and the public sector', London: The Carbon Trust.

Cole, M.A. and R.J.R. Elliott (2003): 'Do environmental regulations influence trade patterns? Testing old and new trade theories' The World Economy **26** (8):1163-1186

Copeland, B.R. and S. Taylor (2004): 'Trade, growth and the environment', Journal of Economic Literature, **XLII**: 7–71

Department for Environment, Food and Rural Affairs (2006): 'Synthesis of climate change policy evaluations' April. London: Defra.

Demailly, D. and P. Quirion (2006): 'CO_2 abatement, competitiveness and leakage in the European cement industry under the EU ETS: grandfathering versus output-based allocation' April, CESifo, Venice: Venice International University.

Ederington, J. and J. Minier (2000): 'Environmental regulation and trade flows', Journal of Economic Literature, Jan 19 2001, available from http://fmwww.bc.edu/RePEc/es2000/1507.pdf

Ederington, J. and J. Minier (2003): 'Is environmental policy a secondary trade barrier? An empirical analysis'. Canadian Journal of Economics, **36**(1): 137-154

Frontier Economics (2006): 'Competitiveness impacts of the EU ETS'.

Greenstone, M. (2002): 'The Impacts of environmental regulations on industrial activity: evidence from the 1970 and 1977 Clean Air Act Amendments and the Census of Manufactures', Journal of Political Economy, **110**: 1175–1219

Grubb, M. (2004): Implications of EU ETS for competitiveness of energy-intensive industry. Presentation at IEA/IETA/EPRI workshop on Greenhouse-Gas Emissions Trading, Paris, 4-5 October 2004.

Grubb, M., and K. Neuhoff (2006): 'Allocation and competitiveness in the EU emissions trading scheme: policy overview', Climate Policy **6**: 7–30

Henderson, D.J. and D.L. Millimet (2001): 'Pollution abatement costs and foreign direct investment inflows to U.S. states: a nonparametric reassessment' Review of Economics and Statistics Vol. **84**(4): 691-703

Helliwell, J.F. (1998): 'How much do national borders matter?' Washington, DC: Brookings Institution Press.

IEA (2005) ‘CO_2 Emissions from fuel combustion 1971-2003’, OECD/IEA, Paris

Jeppesen, T., J.A. List and H. Folmer (2002): 'Environmental regulations and new plant location decisions: evidence from a Meta-Analysis' Journal of Regional Science **42**:19 - February 2002

Klepper, G. and S. Peterson (2004): 'The EU emissions trading scheme allowance prices, trade flows and competitiveness effects' European Environment, **14**(4), 2004. Pages 201-218 Kiel Institute for World Economics, Germany.

Krugman, P. (1994): 'Competitiveness: a dangerous obsession', Foreign Affairs, March.

Levinson, A. and S. Taylor (2003): 'Trade and the environment: unmasking the pollution haven hypothesis' Georgetown University Working Paper Washington, DC: Georgetown University.

Low, P. and A. Yeats (1992): 'Do ‘dirty’ industries migrate?', in P. Low (ed.), International trade and the environment, Washington, DC: World Bank Discussion Paper **159** pp. 89–104

Mani M, and D. Wheeler (1997): 'In search of pollution havens? Dirty industry migration in the world economy', World Bank working paper #16. Washington, DC: World Bank.

McCallum, J. (1995): 'National borders matter: Canada-U.S. regional trade patterns', American Economic Review, American Economic Association, vol. **85**(3): 615-23, June.

Newbery, D.M. (2003): 'Sectoral dimensions of sustainable development: energy and transport', available from http://www.unece.org/ead/sem/sem2003/papers/newbery.pdf

Neuhoff ,K., J. Barquin, M. Boots, et al. (2004): 'Network constrained models of liberalized electricity markets: the devil is in the details. Internal report', Energy research Centre of the Netherlands (ECN), Amsterdam: Petten.

Neuhoff, K. (2006): 'The EU ETS: allocation, competitiveness and longer term design options', submission to Stern Review.

Nitsch, V. and H. Berger (2005): 'Zooming out: the trade effect of the euro in historical perspective'. CESifo Working Paper Series No. 1435.

Oxera (2004): 'CO_2 Emissions Trading: How will it affect UK Industry?' Report prepared for The Carbon Trust, Oxford: Oxera.

Oxera (2006): 'Modelling the competitiveness impact of policy proposals arsing from the Energy Review?' Report prepared for the Department of Trade and Industry, Oxford: Oxera.

Oates, W., Palmer and Portney (1995): 'Tightening environmental standards: the benefit-cost or the no-cost paradigm?' Journal of Economic Perspectives **9**(4), Autumn: 119-132

Reinaud, J. (2004): 'Industrial competitiveness under the European Union Emissions Trading Scheme', Paris: IEA.

Sijm, J.P.M., S.J.A. Bakker, Y.H.W. Chen Harmsen and W. Lise (2005): 'CO_2 price dynamics: The implications of EU emissions trading for the price of electricity', Energy research Centre of the Netherlands (ECN), Amsterdam: Petten.

Smita, B., S.B. Brunnermeier and A. Levinson (2004): 'Examining the evidence on environmental regulations and industry' Location Journal of Environment & Development, **13**(1): 6-41 March

Trefler, D. (1993): 'Trade liberalization and the theory of endogenous protection: an econometric study of US import policy', Journal of Political Economy. **101**(1): 138–60

Williams, E., K. Macdonald and V. Kind (2002): 'Unravelling the competitiveness debate', European Environment **12**(5): 284 - 290 in Special Issue: Environmental Policy in Europe: Assessing the Costs of Compliance Williams E (ed.).

United Nations Development Programme (2005): 'International co-operation behind national borders: an inventory of domestic policy measures aimed at internalising cross-border spillovers adversely affecting the global environment', UNDP Office of Development Studies, New York June 28, available from http://www.thenewpublicfinance.org/background/domestic_spillovers.pdf

Xing, Y. and C.D. Kolstad (2002): 'Do lax environmental regulations attract foreign investment?' Environmental & Resource Economics, **21**(1): 1-2

Annex table 11A.1 Key statistics for 123 UK production sectors (ranked by carbon intensity).[18]

	Carbon intensity (ppt change at £70/tC)	Energy % total costs	Export and import intensity*	Export and import intensity* Non-EU	Percent total UK output
Metal ores extraction	0.00	0.00	67.17	62.86	0.00
Private households with employed persc	0.00	0.00	0.78	0.33	0.50
Financial intermediation □services indire	0.00	0.00	23.82	10.75	-4.68
Letting of dwellings	0.03	0.07	1.10	0.47	7.90
Owning and dealing in real estate	0.08	0.23	0.35	0.20	1.89
Estate agent activities	0.11	0.29	0.11	0.06	0.50
Membership organisations nec	0.14	0.37	0.00	0.00	0.59
Legal activities	0.16	0.43	11.04	6.58	1.39
Market research, management consulta	0.17	0.46	9.44	5.58	1.15
Architectural activities and technical con	0.17	0.47	15.31	8.98	1.95
Accountancy services	0.20	0.53	6.77	3.96	0.99
Other business services	0.20	0.55	36.76	21.98	3.53
Computer services	0.23	0.60	13.32	5.76	2.93
Insurance and pension funds	0.24	0.67	10.15	8.10	2.36
Other service activities	0.25	0.68	2.28	1.16	0.64
Recreational services	0.26	0.64	18.47	10.64	2.87
Health and veterinary services	0.26	0.59	1.49	0.63	4.99
Advertising	0.27	0.72	11.46	6.53	0.67
Footwear	0.27	0.60	46.59	21.14	0.03
Banking and finance	0.27	0.78	7.66	4.56	4.05
Education	0.28	0.68	2.88	1.57	6.01
Auxiliary financial services	0.30	0.73	56.36	35.31	0.88
Transmitters for TV, radio and phone	0.30	0.64	100.70	24.66	0.14
Telecommunications	0.31	0.82	9.28	4.27	2.29
Receivers for TV and radio	0.31	0.63	47.26	24.36	0.08
Social work activities	0.31	0.84	0.03	0.02	1.80
Construction	0.32	0.77	0.23	0.09	6.20
Office machinery & computers	0.33	0.69	81.43	31.86	0.24
Tobacco products	0.33	0.84	15.53	8.03	0.12
Ancillary transport services	0.33	0.97	8.03	3.94	1.81
Medical and precision instruments	0.35	0.80	61.60	33.79	0.56
Pharmaceuticals	0.36	0.77	77.84	31.70	0.64
Leather goods	0.38	0.82	62.28	34.31	0.02
Aircraft and spacecraft	0.41	0.90	97.80	64.35	0.54
Research and development	0.42	1.10	46.57	27.48	0.42
Motor vehicle distribution and repair, aut	0.43	1.22	1.04	0.48	2.24
Renting of machinery etc	0.45	1.25	4.87	2.48	1.07
Printing and publishing	0.45	0.90	14.87	7.02	1.64
Jewellery and related products	0.45	0.89	69.70	54.02	0.04
Retail distribution	0.47	1.26	1.68	0.70	5.73
Confectionery	0.47	0.80	17.80	4.48	0.22
Other transport equipment	0.47	1.10	25.34	12.58	0.10
Hotels, catering, pubs etc	0.48	1.26	19.02	8.38	3.32
Postal and courier services	0.48	1.37	5.69	2.71	0.86
Electronic components	0.49	0.89	88.97	40.31	0.13
Electrical equipment nec	0.49	1.10	55.50	24.19	0.21
Wearing apparel and fur products	0.49	1.02	36.55	22.00	0.17
Public administration and defence	0.49	1.31	0.96	0.58	5.12
Soap and toilet preparations	0.51	1.15	30.60	8.91	0.20
Motor vehicles	0.52	1.10	61.50	14.54	0.85
Sewage and sanitary services	0.54	1.47	2.33	1.15	0.67
Railway transport	0.56	1.40	11.11	4.67	0.29
Made-up textiles	0.56	1.30	20.02	12.84	0.07
Cutlery, tools etc	0.56	1.27	54.00	22.75	0.15
Other food products	0.61	1.47	28.70	7.94	0.26
Electric motors and generators etc	0.61	1.42	65.78	32.83	0.23
Furniture	0.62	1.48	21.64	8.29	0.37
Agricultural machinery	0.63	1.48	64.12	19.21	0.05
Machine tools	0.64	1.40	74.32	33.24	0.07
General purpose machinery	0.65	1.56	56.89	22.56	0.40
Weapons and ammunition	0.65	1.31	25.19	14.51	0.06
Insulated wire and cable	0.67	1.37	53.54	24.58	0.04
Soft drinks and mineral waters	0.67	1.44	16.32	3.93	0.10
Special purpose machinery	0.68	1.59	72.01	35.36	0.27

…/(continued) key statistics for 123 production sectors.

---

[18] by 123 industry Standard Industrial Classification (SIC) level

	Carbon intensity (ppt change at £70/tC)	Energy % total costs	Export and import intensity*	Export and import intensity* Non-EU	Percent total UK output
Meat processing	0.70	1.80	21.72	4.83	0.34
Bread, biscuits etc	0.70	1.60	14.22	2.72	0.32
Mechanical power equipment	0.71	1.51	79.07	41.72	0.26
Knitted goods	0.72	1.48	74.07	40.57	0.04
Domestic appliances nec	0.73	1.76	34.84	13.75	0.11
Alcoholic beverages	0.73	1.71	29.24	13.36	0.29
Paints, varnishes, printing ink etc	0.74	1.67	29.78	8.75	0.12
Rubber products	0.76	1.70	52.40	17.45	0.16
Wood and wood products	0.77	1.95	32.75	10.07	0.28
Sports goods and toys	0.78	1.94	20.48	12.46	0.05
Water supply	0.80	1.56	0.42	0.21	0.30
Pesticides	0.80	1.83	77.22	30.00	0.05
Grain milling and starch	0.81	2.01	22.74	5.38	0.10
Metal boilers and radiators	0.81	1.78	31.36	7.21	0.07
Wholesale distribution	0.82	2.48	-	-	4.41
Textile fibres	0.87	1.68	41.41	18.12	0.03
Other metal products	0.88	2.03	42.92	18.03	0.24
Plastic products	0.90	1.99	33.69	11.10	0.63
Dairy products	0.91	2.56	21.26	3.66	0.14
Other textiles	0.93	1.85	55.12	19.46	0.05
Other chemical products	0.96	2.22	84.83	34.01	0.17
Carpets and rugs	0.97	2.23	19.26	4.09	0.03
Miscellaneous manufacturing nec & rec	0.97	2.39	22.33	13.03	0.20
Animal feed	0.99	2.34	14.74	3.35	0.07
Fish and fruit processing	0.99	2.56	29.87	12.38	0.20
Metal forging, pressing, etc	1.03	2.46	0.00	0.00	0.46
Textile weaving	1.04	1.78	77.76	36.85	0.03
Shipbuilding and repair	1.05	2.36	44.94	28.82	0.10
Ceramic goods	1.08	2.42	42.51	18.75	0.08
Structural metal products	1.09	2.47	13.27	4.56	0.30
Paper and paperboard products	1.17	2.02	15.19	3.99	0.28
Coal extraction	1.22	7.24	33.24	24.76	0.05
Non-ferrous metals	1.32	2.36	73.75	36.90	0.10
Agriculture	1.37	3.96	27.99	11.34	0.96
Metal castings	1.40	2.84	0.00	0.00	0.07
Forestry	1.44	4.18	21.64	6.90	0.03
Glass and glass products	1.53	3.44	33.62	9.55	0.14
Water transport	1.65	5.26	81.65	28.76	0.24
Articles of concrete, stone etc	1.73	2.96	15.97	4.67	0.25
Plastics & synthetic resins etc	1.85	4.57	62.56	15.31	0.12
Oil and gas extraction	1.89	5.73	53.30	30.28	2.06
Textile finishing	1.95	3.34	1.76	0.80	0.03
Other mining and quarrying	2.03	4.64	88.90	61.53	0.16
Industrial gases and dyes	2.03	4.31	49.69	20.32	0.09
Man-made fibres	2.21	4.60	88.19	24.96	0.02
Other land transport	2.21	7.04	7.74	2.33	1.94
Sugar	2.37	3.20	28.83	22.36	0.04
Organic chemicals	2.38	6.27	86.31	31.19	0.17
Air transport	2.39	7.64	53.03	23.82	0.55
Pulp, paper and paperboard	2.42	4.23	66.07	16.52	0.10
Inorganic chemicals	2.58	5.64	34.51	11.75	0.06
Iron and steel	2.69	7.02	55.40	18.32	0.12
Structural clay products	2.73	6.61	3.78	0.63	0.04
Oils and fats	2.86	5.87	38.48	14.49	0.02
Fishing	4.28	12.78	40.35	14.74	0.04
Fertilisers	4.61	13.31	25.69	9.54	0.02
Cement, lime and plaster	9.00	5.00	8.11	1.20	0.05
Electricity production and distribution	16.07	26.70	1.35	0.11	1.08
Refined petroleum	23.44	72.83	25.66	11.75	0.27
Gas distribution	25.36	42.90	0.32	0.18	0.36

*Trade intensity defined as total and non-EU exports of goods and services as a percentage of total supply of goods and services, plus non-EU imports of goods and services as a percentage of total demand for goods and services. Output is defined as gross, so the maximum value attainable is 200.

12 Opportunities and Wider Benefits from Climate Policies

Key Messages

The transition to a low-emissions global economy will open many 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.

Financial markets also face big opportunities to develop new trading and financial instruments across a broad range including carbon trading, financing clean energy, greater energy efficiency, and insurance.

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

Policies on climate change can also help to achieve other objectives, including enhanced energy security and environmental protection. These co-benefits can significantly reduce the overall cost to the economy of reducing greenhouse gas emissions. There may be tensions between climate change mitigation and other objectives, which need to be handled carefully, but as long as policies are well designed, the co-benefits will be more significant than the conflicts.

12.1 Introduction

Climate change policies will lead to structural shifts in energy production and use, and in other emissions-intensive activities. Whilst the previous chapters focused on the resource costs and competitiveness implications of this change, this chapter considers the opportunities that this shift will create. This is discussed in Section 12.2.

In addition, climate change policies may have wider benefits, which narrow cost estimates will often fail to take into account. Section 12.3 looks at the ways in which climate change policies have wider benefits through helping to root out existing inefficiencies at the company or country level.

Section 12.4 considers how climate policies can contribute to other energy policy goals, such as enhanced energy security and lower air pollution. Conversely, policies aimed at other objectives can be tailored to help to make climate change policies more effective. Energy market reform aimed at eliminating energy subsidies and other distortions is an important example, and is considered in Section 12.5.

In other areas, there may be tensions. The use of coal in certain major energy-using countries, for instance, presents challenges for climate change mitigation – although the use of carbon capture and storage can sustain opportunities for coal. Climate change mitigation policies also have important overlaps with broader environmental protection policies, which are discussed in Section 12.6.

Thinking about these issues in an integrated way is important in understanding the costs and benefits of action on climate change. Policymakers can then design policy in a way that avoids conflicts, and takes full advantage of the significant co-benefits that are available.

12.2 Opportunities from growing markets

Markets for low-carbon energy sources are growing rapidly

Whilst some carbon-intensive activities will be challenged by the shift to a low-carbon economy, others will gain. Enormous investment will be required in alternative technologies and processes. Supplying these will create fast-growing new markets, which are potential sources of growth for companies, sectors and countries.

The current size of the market for renewable energy generation products alone is estimated at $38 billion, providing employment opportunities for around 1.7 million people. It is a rapidly growing market, driven by a combination of high fossil fuel prices, and strong government policies on climate change and renewable energy. Growth of the sector in 2005 was 25%[1].

Within this overall total, some markets are growing at an even more rapid rate. The total global installed capacity of solar PV rose by 55% in 2005, driven by strong policy incentives in Germany, Japan and elsewhere[2], and the market for wind power by nearly 50%[3]. The market capitalisation of solar companies grew thirty-eightfold to $27 billion in the 12 months to August 2006, according to Credit Suisse[4]. Growth in biofuels uptake was not quite as rapid, but there was still a 15% rise to 2005, making the total market over $15 billion.

Growth rates in these markets will continue to be strong, creating opportunities for business and for employment opportunities.

Looking forward, whilst some of these very rapid rates may not be sustained, policies to tackle climate change will be a driver for a prolonged period of strong growth in the markets for low-carbon energy technology, equipment and construction. The fact that governments in many countries are also promoting these new industries for energy security purposes (Section 12.5) will only strengthen this effect.

One estimate of the future market for low-carbon energy technologies can be derived from the IEA's Energy Technology Perspectives report. This estimates the total investment required in low-carbon power generation technologies in a scenario where total energy emissions are brought back down to today's levels by 2050[5]. It finds that cumulative investment in these technologies by 2050 would be over $13 trillion, accounting for over 60% of all power generation by this date. The annual market for low-carbon technologies would then be over $500bn per year. Other estimates are still higher: recent research commissioned by Shell Springboard suggests that the global market for emissions reductions could be worth $1 trillion cumulatively over the next five years, and over $2 trillion per year by 2050.[6]

The massive shift towards low-carbon technologies will be accompanied by a shift in employment patterns. If it is assumed that jobs rise from the current level of 1.7 million in line with the scale of investment, over 25 million people will be working in these sectors worldwide by 2050.

Climate change also presents opportunities for financial markets

Capital markets, banks and other financial institutions will have a vital role in raising and allocating the trillions of dollars needed to finance investment in low-carbon technology and the companies producing the new technologies. The power companies will also require access to large, long-term funds to finance the adoption of new technology and methods, both

---

[1] REN21 (2006).
[2] Renewables Global Status Report, 2006 update: REN21.
[3] Clean Edge (2006).
[4] Quoted in Business Week, "Wall Street's New Love Affair", August 14 2006.
[5] This investment excludes the transport sector, but includes nuclear, hydropower, and carbon capture and storage.
[6] Shell Springboard (2006). This is an estimate of total expenditure on carbon abatement, and so would include all emission reduction sources. Figures are based on a central scenario.

to conform to new low-carbon legislation and to satisfy rising global power demand from growing populations enjoying higher living standards.

The new industries will create new opportunities for start-up, small and medium enterprises[7] as well as large multinationals. Linked to this, specialist funds focusing on clean energy start-ups and other specialist engineering, research and marketing companies are emerging. Clean technology investment has already moved from being a niche investment activity into the mainstream; clean technology was the third largest category of venture capital investment in the US in the second quarter of 2006[8].

The insurance sector will face both higher risks and broader opportunities, but will require much greater access to long-term capital funding to be able to underwrite the increased risks and costs of extreme weather events[9]. Higher risks will demand higher premiums and will require insurance companies to look hard at their pricing; of what is expected to become a wider range of weather and climate-related insurance products[10].

The development of carbon trading markets also presents an important opportunity to the financial sector. Trading on global carbon markets is now worth over $10bn annually with the EU ETS accounting for over $8bn of this[11]. Expansions of the EU ETS to new sectors, and the likely establishment of trading schemes in other countries and regions is expected to lead to a big growth in this market. Calculations by the Stern Review as a hypothetical exercise show that if developed countries all had carbon markets covering all fossil fuels, the overall market size would grow 200%, and if markets were established in all the top 20 emitting countries, it would grow 400% (the analysis behind these numbers can be found in Chapter 22).

This large and growing market will need intermediaries. Some key players are set out in Box 12.1. The City of London, as one of the world's leading financial centres, is well positioned to take advantage of the opportunities; the most actively traded emissions exchange, ECX, is located and cleared in London, dealing in more than twice the volume of its nearest competitor[12].

---

[7] See, for instance, Shell Springboard (2006).
[8] Cleantech Venture Network (2006).
[9] Salmon and Weston (2006).
[10] See Ceres (2006) .
[11] World Bank (2006a).
[12] CEAC (2006).

Box 12.1 Financial intermediaries and climate change

The transition involved in moving to a low-carbon economy creates opportunities and new markets for financial intermediaries. Emissions trading schemes in particular require a number of key financial, legal, technical and professional intermediaries to underpin and facilitate a liquid trading market. These include:

Corporate and project finance: trillions of dollars will be required over the coming decades to finance investments in developing and installing new technologies. Creative new financing methods will be needed to finance emission reduction projects in the developing world. And emissions trading will require the development of services needed to manage compliance and spread best practice.

MRV services (monitoring, reporting and verification): these are the key features for measuring and auditing emissions. MRV services are required to ensure that one tonne of carbon emitted or reduced in one place is equivalent to one tonne of carbon emitted or reduced elsewhere.

Brokers: are needed to facilitate trading between individual firms or groups within a scheme, as well as offering services to firms not covered by the scheme who can sell emission reductions from their projects.

Carbon asset management and strategy: reducing carbon can imply complex and inter-related processes and ways of working at a company level. New opportunities will arise for consultancy services to help companies manage these processes.

Registry services: these are needed to manage access to and use of the registry accounts that hold allowances necessary for surrender to the regulator.

Legal services: these will be needed to manage the contractual relationships involved in trading and other schemes.

Trading services: the transition to a low carbon economy offers growing opportunities for trading activities of all kinds, including futures trading and the development of new derivates markets.

Companies and countries should position themselves now to take advantage of these opportunities

There are numerous examples of forward-looking companies which are now positioning themselves to take advantage of these growth markets, ranging from innovative high-technology start-up firms to some of the world’s largest companies.

Likewise, governments can seek to position their economy to take advantage of the opportunities. Countries with sound macroeconomic management, flexible markets, and attractive conditions for inward investment can hope to win strong shares of the growing clean energy market. But particular countries may also find that for historical or geographical reasons, or because of their endowment of scientific or technical expertise, they have advantages in the development of particular technologies. There may be grounds for government intervention to support their development, particularly if promising technologies are far from market and needs to be scaled up to realise their full potential – Chapter 16 discusses how market failures and uncertainties over future policy justify action in this area.

Implementing ambitious climate change goals and policies may also help to create a fertile climate for clean energy companies. Hanemann et. al. (2006) analysed the economic impact of California taking the lead in adopting policies to reduce GHG emissions. They concluded that, if it acts now, California can gain a competitive advantage, by becoming a leader in the new technologies and industries that will develop globally as international action to curb GHG emissions strengthens. They estimate that this could increase gross state product by $60 billion, and create 20,000 new jobs, by 2020.

12.3 Climate change policy as a spur to efficiency and productivity

Climate change policies can be a general spur to greater efficiency, cost reduction and innovation for the private sector

Predictions of the costs of environmental regulations often turn out to be overestimates. Hodges (1997) compared all cases of emission reduction regulations for which successive cost estimates were available, a dozen in total. He found that in all cases except one (CFCs where costs were only 30% below expectations due to the accelerated timetable for phase-out of the chemical), the early estimates were at least double the later ones, and often much greater.

One example is the elimination of CFCs in car air conditioners. Early industry estimates suggested this would increase the price of a new car by between \$650 and \$1200. By 1997, the cost was \$40 to \$400[13].

When such numbers come to light, companies are often accused of inflating initial cost estimates to support their lobbying efforts. But there is a more positive side to the story. The dramatic reduction in costs is often a result of the process of innovation, particularly when a regulatory change results in a significant increase in the scale of production.

And the process of complying with new policies may reveal hidden inefficiencies which firms can root out, saving money in the process (Box 12.2).

Box 12.2 Reducing Business Costs Through Tackling Climate Change

An increasing number of private and public sector organisations are discovering the potential to reduce the cost of goods and services they supply to the market. A study of 74 companies drawn from 18 sectors in 11 countries including North America, Europe, Asia, and Australasia revealed gross savings of \$11.6 billion, including[14]:

- BASF, the multi-national conglomerate and chemical producer, has reduced GHG emissions by 38% between 1990 and 2002 through a series of process changes and efficiency measures which cut annual costs by 500 million euros at one site alone;

- BP established a target to reduce GHG emissions by 10% on 1990 levels by 2010, which it achieved nine years ahead of schedule, while delivering around \$650 million in net present value savings through increased operational efficiency and improved energy management. Between 2001 and 2004, the organisation contributed a further 4MtC of emission reductions through energy and flare reduction projects. \$350 million investment in energy efficiency is planned over 5 years from 2004.

- Kodak began tracking its greenhouse gas emissions in the 1990s, and set five-year goals for emissions reductions. To help to achieve this, the company performed short, focused energy assessments – "Energy Kaizens" – across different areas of its business, aimed at reducing waste. Between 1999 and 2003, this and other initiatives resulted in overall savings of \$10 million.

Tackling climate change may also have more far-reaching effects on the efficiency and productivity of economies. Schumpeter (1942)[15] developed the concept of "creative destruction" to describe how breakthrough innovations could sweep aside the established economic status quo, and unleash a burst of creativity, investment and economic growth which ushers in a new socio-economic era. Historical examples of this include the introduction of the railways, the invention of electricity, and more recently, the IT revolution. Dealing with

---

[13] American Prospect, "Polluted Data", November 1997.

[14] The Climate Group (2005).

[15] See also Aghion and Howitt (1999).

climate change will also involve fundamental changes worldwide, particularly to energy systems.

In particular, the shift to low-carbon energy technologies will result in a transformation of energy systems; the implications of this are explored in the following sections.

12.4 The links between climate change policy and other energy policy goals

Climate change policies cannot be disconnected from policies in other areas, particularly energy policy. Where such synergies can be found, they can reduce the effective cost of emissions reductions considerably. There may also be tensions in some areas, if climate change policies undermine other policy goals. But as long as policies are well designed, the co-benefits should outweigh the conflicts.

Climate change and energy security drivers will often work in the same direction, although there are important exceptions

Energy security is a key policy goal for many developed and developing countries alike. Although often understood as referring mainly to the geopolitical risks of physical interruption of supply, a broader definition would encompass other risks to secure, reliable and competitive energy, including problems with domestic energy infrastructure.

Energy efficiency is one way to meet climate change and energy security objectives at the same time. Policies to promote efficiency have an immediate impact on emissions. More efficient use of energy reduces energy demand and puts less pressure on generation and distribution networks and lowers the need to import energy or fuels. For developing countries in particular, who often have relatively low energy efficiency, this is an attractive option. Indirectly, they also help with local air pollution, by limiting the growth in generation.

Improving efficiency within the power sector itself has similar effects. Box 12.3 gives an example of the scale of the potential to reduce emissions from making fossil fuel production processes more efficient.

Box 12.3 Economic opportunities from reducing gas-flaring in Russia

In total, leaks from the fossil fuel extraction and distribution account for around 4% of global greenhouse gas emissions. Within this, gas flaring – the burning of waste gas from oil fields, refineries and industrial plants – accounts for 0.4% of global emissions. Increasingly, there has been a move to capture these gases, driven by economic as much as environmental reasons. This is by no means universal, and in some countries the potential for emissions savings in this area remains significant.

The post-Soviet collapse of Russia's energy-intensive economy cut carbon emissions and left it with a surplus of transferable emission quotas under the Kyoto protocol. Decades of under-investment, however, mean that current 6-7 per cent GDP growth, spurred by higher energy and commodity prices, is both raising emissions and putting pressure on the infrastructure. Sustaining growth requires very large energy and related infrastructure investment. In June 2006 the government approved a $90bn investment programme to replace ageing coal and nuclear generating plants, increase generating capacity and strengthen the grid system.

A recent IEA report[16] on Russian gas flaring, however, indicates that without accompanying price and structural reforms, especially in the gas sector, investment alone is unlikely to deliver the full potential for efficiency gains or reductions in GHGs.

The report indicates that low prices for domestic gas, coupled with Gazprom's monopoly over access to both domestic and export gas pipelines and the high levels of waste and inefficient technology, restrict its ability to satisfy rising export and domestic demand, and to reduce both gas losses and GHG emissions.

In 2004 Gazprom lost nearly 70 billion cubic metres (bcm) of the nearly 700bcm of natural gas which flowed through its network because of leaks and high wastage from inefficient compressors. Gas related emissions amounted to nearly 300 MtCO2e of GHG, including 43 MtCO2e from the 15bcm of gas flared off, mainly by oil companies unable to gain access to Gazprom's pipes. On this basis, Russia accounted for around ten per cent of natural gas flared off globally every year. However, an independent study conducted by the IEA and the US National Oceanic and Atmospheric administration, calibrated from satellite images of flares in the main west Siberian oilfields, indicated however that up to 60bcm of gas may be lost through flaring – over a third of the estimated global total[17].

Gas flaring represents a clear illustration of the potential efficiency gains from new technology linked to more rational pricing policies and other structural reforms. These would also yield significant climate change mitigation benefits.

A more diverse energy mix can be an effective hedge against problems in the supply of any single fuel. As climate change policy tends to encourage a more diverse energy mix, it is generally good for energy security. And conversely, policies carried out for energy security reasons may have benefits for climate change. The expansion of a range of sources of renewable power and, where appropriate, of nuclear energy can reduce the exposure of economies to fluctuations in fossil fuel prices, as well as reducing import dependence.

Coal is an important exception to this rule. Coal is much more carbon intensive than other fossil fuels: coal combustion emits almost twice as much carbon dioxide per unit of energy as does the combustion of natural gas (the amount from crude oil combustion falls between coal and natural gas[18]). Many major energy-using countries have abundant domestic coal supplies, and hence see coal as having an important role in enhancing energy security. China, in particular, is already the world's largest coal producer; its consumption of coal is likely to double over the 20 years between 2000 and 2020[19].

---

[16] IEA (2006).
[17] IEA (2006).
[18] Energy Information Administration (1993).
[19] Chinese Academy of Social Sciences (2006).

As well as using coal directly for energy production, coal-producing countries including the US, Australia, China and South Africa are investing in coal-to-liquids technology, which would allow them to reduce their dependence on imported oil and use domestic coal to meet some of the demand for transport fuel. But it has been estimated that "well-to-wheel" (full lifecycle) emissions from the production and use of coal-to-liquids in road transport are almost double those from using crude oil[20].

However, extensive deployment of carbon capture and storage (as discussed in Chapter 9), can reconcile the use of coal with the emissions reductions necessary for stabilising greenhouse gases in the atmosphere.

Supporting sufficient investment in generation and distribution capacity also requires a sound framework capable of bringing forward required investment. Clear, long-term credible signals about climate policy are a critical part of this. If there is uncertainty about the future direction of climate change policy, energy companies may delay investment, with serious consequences for security of supply. This is discussed in more detail in Chapter 15.

Access to energy is a priority for economic development

There are currently 1.6 billion people in the world without access to modern energy services[21]. This restricts both their quality of life, and their ability to be economically productive. Providing poor people with access to energy is a very high priority for many developing countries, and can have significant co-benefits in reducing local pollution, as the next section discusses.

Increasing the number of energy consumers, by providing access to energy, would tend to push emissions upwards. But well-designed policies present opportunities for meeting several objectives at once. New renewable technologies, developed with climate change objectives in mind, can help to overcome barriers to access to energy. Microgeneration technologies (see Box 17.3 in Chapter 17) such as small-scale solar and hydropower, in particular, remove the need to be connected to the grid, and so help raise availability and reduce the cost of electrification in rural areas. And as discussed below, the replacement of low-quality biomass energy with modern energy can cut emissions and pollution.

As well as access, affordability is a key issue in both developed and developing countries. Poverty is determined by people's capacity to earn in relation to prices. Energy prices are one significant aspect, along with food and other essentials.

But it is inappropriate to deal with poverty by distorting the price of energy. Addressing income distribution issues directly is more effective. There are a number of ways to achieve this. One is indexing social transfers to a price index, taking account of different consumption patterns of poorer groups in the relevant price index for those groups. Other more direct means include making special transfers to those with special energy needs such as the elderly, and the use of "lifeline tariffs", whereby people using a minimal amount of power pay a sharply reduced tariff for a fixed maximum number of units.

Climate change policies can help to reduce local air pollution, with important benefits for health

Measures to reduce energy use, and to reduce the carbon intensity of energy generation, can have benefits for local air quality. Most obviously, switching from fossil fuels to renewables, or from coal to gas, can significantly the levels of air pollution resulting from fossil fuel burning.

A recent study by the European Environment Agency[22] showed that the additional benefits of an emissions scenario aimed at limiting global mean temperature increase to 2^0C would lead

---

[20] Well-to-wheels emissions from fuels such as gasoline are around 27.5 pounds of CO2 per gallon of fuel. This compares with 49.5 pounds per gallon from coal-to-liquids, assuming the CO2 from the refining process is released into the atmosphere. See Natural Resources Defence Council (2006).

[21] World Bank, "1.6 billion people still lack access to electricity today", press release, 18 September 2006 .

[22] Air Quality and ancillary benefits of climate change, EEA, Copenhagen, 2006

to savings on the implementation of existing air pollution control measures of €10 billion per year in Europe, and additional avoided health costs of between €16-46 billion per year.

Local air pollution has a serious impact on public health and the quality of life. These impacts are particularly severe in developing countries, where only malnutrition, unsafe sex and lack of clean water and adequate sanitation are greater health threats than indoor air pollution[23]. In China, a recent study[24] showed that for CO_2 reductions up to 10-20%, air pollution and other benefits more than offset the costs of action.

Forthcoming analysis from the IEA (Box 12.4) shows that combustion of traditional biomass for cooking and heating in developing countries is associated with high GHG emissions and adverse indoor air quality and health impacts, which switching to a cleaner fuel could reduce.

Box 12.4 Use of traditional biomass in developing countries

In developing countries, 2.5 bn people depend on traditional biomass such as fuel wood and charcoal as their primary fuel for cooking and heating because it is a cheap source of fuel. The emissions associated with this biomass are relatively high because it is not combusted completely or efficiently. Aside from the climate change impact, combustion of biomass is associated with a range of detrimental effects on health, poverty and local environment including:-

- Smoke from biomass from cooking and heating was estimated to cause 1.3 m premature deaths in 2002. Women and children are most severely affected because they spend most time in the home doing domestic tasks. More than half the deaths are children because their immune systems are poorly equipped to deal with the local air pollution.
- Time spent collecting the biomass is time that could otherwise be spent by women or children in education or other productive work. The collection of biomass may also involve hard physical labour that deteriorates the health of the women and children doing it.
- Collection of biomass causes localised deforestation and land degradation. If animal dung is used as a fuel rather than a fertiliser then soil fertility suffers. The widespread use of fuel wood and charcoal can mean local resources getting used up so people have to travel further to collect it.

Switching away from traditional biomass towards modern, cleaner cooking fuels can save GHG emissions and reduce the health, poverty and local environment concerns outlined above. The UN Millennium Project has adopted a target of reducing by 50% the number of households using traditional biomass as their primary fuel by 2015; this means giving an extra 1.3 bn people access to clean fuels by this date. If this were achieved by switching these users to liquid petroleum gas, it would cost $1.5 bn per year for new stoves and canisters, increase global demand for oil by just 0.7% in 2015, and result in a small reduction in GHG emissions.

Source: IEA (in press).

Sometimes climate change objectives will conflict with local air quality aims. This is a particular issue in transport. In road transport, switching from petrol to diesel reduces CO_2 emissions, but increases local air pollution (PM10 and NOx emissions). High blends of biodiesel can also emit slightly more NOx than conventional diesel. The US and EU are in the process of implementing stronger policies to reduce CO_2 emissions from diesel vehicles, although this will take time to have an effect.

---

[23] WHO (2006).

[24] Aunan et al (2006)

In the case of aviation, there are multiple links between objectives[25]. One of the ways of achieving CO_2 improvements in aircraft is to increase combustion temperatures in engines. However, this increases levels of NOx, an important local air pollutant. Other measures to improve fuel efficiency and CO_2 performance, such as reducing aircraft weight, have benefits for local air pollution. And there are complex relationships between gases emitted at altitude – there are suggestions, for instance, that more modern engines have a greater tendency to produce condensation trails, which intensify warming effects (see Box 15.6, Chapter 15). Further technological advances in aircraft construction will be important in meeting both climate change and air pollution objectives simultaneously.

Policies to meet air pollution and climate change goals are not always compatible. But if governments wish to meet both objectives together, then there can be considerable cost savings compared to pursuing both separately.

12.5 The role of pricing and regulatory reforms in the energy markets

Pricing and regulatory reforms in the energy markets are important both for effective climate change policy, and for long-term productivity and efficiency

Many countries have a long history of subsidising particular fuels: coal, oil, nuclear power, electricity for rural areas, and more recently renewable energy. With the important exceptions of support mechanisms for R&D and innovation (see Chapter 16), these are a source of economic distortion and loss. Furthermore there has been a strong historical bias toward the more polluting fuels. The liberalisation of energy markets that began to take place in many countries in the late 1980s and early 1990s was seen as a means of reducing these subsidies, which in some cases had reached extraordinary proportions. By 1998 they had declined worldwide, but still amounted to nearly $250 billion per year, of which over $80 billion were in the OECD countries and over $160 billion in developing countries (see Table 12.1). These transfers are on broadly the same scale as the average incremental costs of an investment programme required for the world to embark on a substantial policy of climate change mitigation over the next twenty years (see Chapter 9). The IEA estimate that world energy subsidies were still $250 billion in 2005, of which subsidies to oil products amounted to $90 billion[26].

Table 12.1 Energy Subsidies by Source $ billion (data for 1995-1998 period)

	OECD Countries	Countries not in OECD	Total
Coal	30	23	53
Oil	19	33	52
Gas	8	38	46
All fossil fuels	**57**	**94**	**151**
Electricity	-	48	48
Nuclear	16	?	16
Renewables and energy efficiency	9	?	9
Cost of bankruptsy bail-out	0	20	20
Total	**82**	**162**	**244**

Source: de Moor (2001) and van Beers and de Moor (2001). Another perspective on subsidies is provided by Myers, N. and J. Kent (1998) 'Perverse Subsidies: Tax $s Undercutting our Economies and Environment Alike', Winnipeg, IISD.

Applied in the form of tax credits and incentives for innovation, subsidies can and do serve an economic purpose. However, the prevailing subsidies are for the most part not applied to this end. The inefficiencies associated with subsidies have been reviewed by economists many times over the past decades, and are simply stated:

---

[25] See European Commission (2005).

[26] IEA (in press).

- subsidies stimulate unnecessary consumption and waste, and more generally are a source of economic inefficiency in that the low price is associated with low benefits on the margin relative to the cost of production;

- tend to benefit the middle and higher income groups, so impacting income distribution in a negative way, particularly in developing countries where poor people lack access to energy;

- by undermining the capacity of the industry to earn returns directly on the basis of cost-reflecting prices, subsidies undermine the managerial (or 'X') efficiency of the industry, and also its capacity to finance its expansion;

- lead to wasteful lobbying and rent-seeking by groups trying to maintain or increase subsidies;

- when applied to fossil fuels subsidies discourage the development of and investment in low carbon alternatives, including investment in carbon capture and storage.

To the extent that climate change policy triggers wider energy reform, it would have great supplementary benefits, as long as the transition is well managed. And for carbon price signals to work well, it is essential that the energy market also works well.

An example of the costs of energy market inefficiencies, and the way in which reforms can deliver environmental and other goals, is given in Box 12.5 for India.

Box 12.5 Fuelling India's growth and development

India's economic growth is constrained by an inadequate power supply that results in frequent blackouts and poor reliability. Subsidised tariffs to residential and agricultural consumers,[27] low investment in transmission and distribution systems, inadequate maintenance, and high levels of distribution losses, theft and uncollected bills place the State Electricity Boards (SEBs, which form the basis of India's power system) under severe financial difficulties.[28] These losses and subsidies are a significant drain on budgets and can result in public spending on vital areas such as health and education being crowded out. Annual power sector losses associated with inefficiencies and theft are estimated at over $5 billion – more than it would cost to support India's primary health care system.[29]

The demand shortages facing India – 56% of Indian households have no electricity supply - create incentives for getting generation plants on line as rapidly as possible. These priorities in turn favour reliable, conventional, coal-fired units.[30] The use of coal for the bulk of electricity generation presents particular challenges. Coal mining is dangerous, and its transportation creates environmental problems of its own. Coal also produces pollutants such as sulphur dioxide that damage local air quality, causing further problems for human health and the environment. These issues are exacerbated by the low energy efficiency of India's coal-fired power plants, combined with India's policies of high import tariffs on high-quality coal and subsidies on low-quality domestic coal. The use of CCS technology will be an important way to reconcile the cost and convenience advantages of coal with environmental goals.

The Government of India has set out an energy policy to help address these constraints and concerns. The broad objective of this policy is to reliably meet the demand for energy services of all sectors at competitive prices, through "safe, clean and convenient forms of energy at the least-cost in a technically efficient, economically viable and environmentally sustainable

---

[27] The tariff structure, for example, violates the fundamental principle of economics whereby tariffs should reflect the actual cost of service. In practice, industry is charged the highest tariff despite having the lease cots of supply, whilst agriculture has the lowest tariff and the highest cost of service.

[28] World Bank (2001).

[29] World Bank (2006b).

[30] World Bank (2006b).

[31] Government of India (2006: xiii).

[32] Government of India (2006).

manner".[31] With sufficient effort made in improving energy efficiency and conservation, for example, the Government of India has stated that it would be possible to reduce the country's energy intensity by up to 25% from current levels.[32] Progress in achieving the goals and objectives of their energy policy, ranging from improving energy efficiency to promoting the use of renewables, will also make a significant contribution to reducing future GHG emissions from India.

12.6 Climate change mitigation and environmental protection

This section looks at the links between climate change and broader environmental protection goals. One area where these links are particularly strong is deforestation. Policies that prevent deforestation can have significant benefits for communities dependant on forests, for water management and biodiversity. Some of these are set out in Box 12.6.

Box 12.6 Co-benefits of ending deforestation

Protection/Preservation of biodiversity: Tropical forests house 70% of the Earth's plants and animals. Without forest conservation, many of the world's plant and animal species face extinction this century. Essential natural resources are found in frontier forests that cannot be recreated.

Research and development: Frontier forests in Brazil, Colombia and Indonesia are home to the greatest plant biodiversity in the world. Destroying these forests destroys the source of essential pharmaceutical ingredients; 40-50% of drugs in the market have an origin in natural products[33], with 42% of the sales of the top 25 selling drugs worldwide either biologicals, natural products, or derived from natural products[34].

Indigenous peoples and sustainability: About 50 million people are believed to be living in tropical forests, with the Amazonian forests home to around 1 million people of 400 different indigenous groups. Forest conservation affects people beyond those who inhabit them. Over 90% of the 1.2 billion people living in extreme poverty depend on forests for some part of their livelihoods[35].

Tourism: Forests provide opportunities for recreation for an increasingly wealthy and urbanised population. Brazil had a five-fold increase in tourists between 1991 and 1999, with 3.5m people visiting Brazil's 150 Conservation Areas.

Consequences for vulnerability to extreme weather events: Forests systems can play an important role in watersheds, and their loss can lead to an increase in flooding. In November 2005 a flash flood occurred in Langkat, Indonesia that killed 103 people with hundreds more missing. The Mount Leuser National Park had lost up to 22% of its forest cover due to logging and, combined with high rainfall, had caused a landslide to occur[36].

In 2004, 3000 people died in Haiti after a tropical storm, while only 18 people across the border in the Dominican Republic died. The difference has been linked to extensive deforestation in Haiti where political turmoil and poverty have lead to the destruction of 98% of original forest cover[37]. Mangrove forests, depleted by 35% (see Millennium Ecosystem Assessment 2005) play an important role in coastal defence, as well as providing important nursery grounds for fish stocks. Areas with healthy mangrove or tree cover were significantly less likely to have experienced major damage in the 2004 tsunami[38].

---

[33] www.fic.nih.gov/programs/research_grants/icbg/index.htm

[34] CBI (2005).

[35] World Bank (2006): 'Forests and Forestry' available from http://web.worldbank.org/WBSITE/EXTERNAL/TOPICS/EXTARD/EXTFORESTS/0,,menuPK:985797~pagePK:149018~piPK:149093~theSitePK:985785,00.html

[36] Jakarta Post (2003): Rampant deforestation blamed for Langkat flash flood. 05/11/2003.

[37] Secretariat of the Convention on Biological Diversity (2006).

[38] Secretariat of the Convention on Biological Diversity (2006).

Reducing GHG emissions from agriculture could also have benefits for local environment and health. For example, in China, nitrous oxide emissions associated with overuse of fertiliser contributes to acid rain, severe eutrophication of the China Sea and damage to health through contamination of drinking water. Cutting these emissions could help to reduce these effects[39].

However, climate change mitigation may, if poorly implemented, undermine sustainable development. Chapter 9 discussed the technical potential of biomass to save emissions in the power, transport, industry and buildings sectors. But if the crops are grown at very large scale through intensive, large-scale monoculture, then this has the potential to cause serious environmental impacts. These may include the increased use of pesticides; a loss of biodiversity and natural habitats[40]; and social problems and displacement of indigenous peoples.

Mitigation policies can also sometimes be designed in a way that helps countries cope with existing climate variability and adapt to future climate change. Better design of building stock, for instance, can both reduce the demand for space heating and cooling and provide greater resilience to a changing climate.

While there are important links between mitigation and development, it is important to assess policy development against the full range of opportunities to meet climate goals and the full range of options to achieve the Millennium Development Goals (see Michaelowa 2005). As with other co-benefits, the key is that well designed policy can realise the synergies between different goals, as well as the limits to this. For example, to improve education levels in developing countries, schools could be supplied with low emission energy supplies, or more trained teachers. Both interventions will be associated with a wide range of different costs and benefits, which should be weighed up when considering which option is preferred.

12.7 Conclusion

Whilst climate change presents clear challenges and costs to the global economy, it also presents opportunities. Markets for clean energy technologies are set for a prolonged period of rapid growth, and will be worth hundreds of billions of dollars a year in a few decades' time. Companies and countries should position themselves to take advantage of these growth markets.

It is also important to consider the wider impacts of climate change policy. As well as helping to root out existing inefficiencies, climate change policy can also help to achieve other policies and goals, particularly around energy policy and sustainable development.

A full understanding of these interlinkeages is key to designing policy in a way that minimises the areas of conflict between goals, and to reap the benefits of the opportunities and synergies that exist.

---

[39] Norse (2006).

[40] See, for instance, European Environmental Bureau (2006).

References

Aghion, P. and P. Howitt (1999): 'On the macroeconomic consequences of major technological change', in General Purpose Technologies and Economic Growth, ed. E. Helpman, Cambridge, MA: MIT Press.

Aunan et al. (2006): ‘Benefits and costs to China of a climate policy’, Environment and Development Economics, accepted for publication

Confederation of British Industry (2005): 'EU market survey natural ingredients for pharmaceuticals' Rotterdam: CBI.

CEAC (2006): “Emissions trading and the City of London”, report to the City of London, September 2006.

Ceres (2006): ‘From Risk to Opportunity: How insurers can proactively and profitably manage climate change’, Ceres, August 2006

Chinese Academy of Social Sciences (2006): available from http://www.hm-treasury.gov.uk/media/5FB/FE/Climate_Change_CASS_final_report.pdf

Clean Edge (2006): 'Clean Energy Trends', San Francisco, Clean Edge Inc., available from http://www.cleanedge.com/reports/trends2006.pdf

Cleantech Venture Network (2006): ‘Cleantech Becomes Third Largest Venture Capital Investment Category with $843 Million Invested in Q2 2006’, Press release August 10 2006

Energy Information Administration (1993): 'Emissions of greenhouse gases in the United States 1985-1990', DOE/EIA-0573, Washington, DC: EIA, p. 16.

European Commission (2005): ‘Giving Wings to Emissions Trading: Inclusion of aviation into the European Emissions Trading System - design and impacts’, European Commission, report reference ENV.C.2/ETU/2004/0074r

European Environmental Bureau (2006): 'Fuelling extinction? Unsustainable biofuels threaten the environment', Brussels: EEB, BirdLife International and European Federation for Transport and the Environment.

Government of India, Planning Commission (2006): 'Integrated Energy Policy: Report of the Expert Committee'. New Delhi: Government of India, Planning Commission, August 2006.

Hanemann M.W. and A.E. Farrell (2006): 'Managing greenhouse gas emissions in California', California: The California Climate Change Center at UC Berkeley.

Hodges, H. (1997): 'Falling prices, cost of complying with environmental regulations almost always less than advertised.' Washington, DC: Economic Policy Institute, available from http://www.epinet.org/briefingpapers/bp69.pdf

International Energy Agency (2006): ‘Optimising Russian natural gas’, Paris: OECD/IEA

International Energy Agency (in press): ‘World Energy Outlook 2006’, Paris: OECD/IEA.

Millennium Ecosystem Assessment (2005): 'Ecosystems and Human Well-being: Synthesis'. Washington, DC: Island Press.

Natural Resources Defence Council (2006): Testimony of David G. Hawkins to the Committee on Energy and Natural Resources, 24 April 2006.

Norse D. (2006): ‘Key trends in emissions from agriculture and use of policy instruments’, available from www.sternreview.org.uk

REN21 (2006): 'Renewables Global Status Report 2006 Update', Washington, DC: REN21 Secretariat and Washington DC: Worldwatch Institute.

Salmon, M. and Weston, S. (2006): ‘Open letter to the Stern Review on the economics of climate change’, available from www.sternreview.org.uk

Schumpeter, J. (1942): 'Capitalism, Socialism and Democracy', New York: Harper.

Secretariat of the Convention on Biological Diversity (2006): 'Global Biodiversity Outlook 2'. Montreal: CBD available from http://www.biodiv.org

Shell Springboard (2006): 'The Business Opportunities for SMEs in tackling the causes of climate change', report by Vivid Economics for Shell Springboard, October 2006.

Swart, R., M. Amann, F. Raes and W. Tuinstra (2004): 'A good climate for clean air: linkages between climate change and air pollution, an editorial essay', Climatic Change Journal, **66**(3): 263-269

The Climate Group (2005), ‘Carbon down profits up – Second Edition 2005’.

World Bank (2006a): 'State and Trends of the Carbon Market', Washington, DC: World Bank.

World Bank (2006b): Clean energy and development: towards an investment framework. Washington, DC: World Bank.

World Bank (2001): Fuelling India’s Growth and development: World Bank support for India’s Energy Sector. Washington, DC: World Bank.

World Health Organisation (2006): ‘Fuel for Life’, Geneva: WHO.

World Resources Institute (2005): 'Growing in the greenhouse: protecting the climate by putting development first' [R. Bradley and K.A. Baumert], Washington, DC: WRI.

13 Towards a Goal for Climate-Change Policy

Key Messages

Reducing the expected adverse impacts of climate change is both highly desirable and feasible. The need for strong action can be demonstrated in three ways: by comparing disaggregated estimates of the damages from climate change with the costs of specific mitigation strategies, by using models that take some account of interactions in the climate system and the global economy, and by comparing the marginal costs of abatement with the social cost of carbon.

The science and economics both suggest that a shared international understanding of the desired goals of climate-change policy would be a valuable foundation for action. Among these goals, aiming for a particular target range for the ultimate concentration of greenhouse gases (GHGs) in the atmosphere would provide an understandable and useful guide to policy-makers. It would also help policy-makers and interested parties at all levels to monitor the effectiveness of action and, crucially, anchor a global price for carbon. Any long-term goal would need to be kept under review and adjusted as scientific and economic understanding developed.

However, the first key decision, to be taken as soon as possible, is that strong action is indeed necessary and urgent. This does not require immediate agreement on a precise stabilisation goal. But it does require agreement on the importance of starting to take steps in the right direction while the shared understanding is being developed.

Measuring and comparing the expected benefits and costs over time of different potential policy goals can provide guidance to help decide how much to do and how quickly. Given the nature of current uncertainties explored in this Review, and the ethical issues involved, analysis can only suggest a range for action.

The current evidence suggests aiming for stabilisation somewhere within the range 450 - 550ppm CO_2e. Anything higher would substantially increase risks of very harmful impacts but would only reduce the expected costs of mitigation by comparatively little. Anything lower would impose very high adjustment costs in the near term for relatively small gains and might not even be feasible, not least because of past delays in taking strong action.

For similar reasons, weak action over the next 20 to 30 years, by which time GHG concentrations could already be around 500ppm CO_2e, would make it very costly or even impossible to stabilise at 550ppm CO_2e. **There is a high price to delay.** Delay in taking action on climate change would lead both to more climate change and, ultimately, higher mitigation costs.

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

Policy should be more ambitious, the more societies dislike bearing risks, the more they are concerned about climate-change impacts hitting poorer people harder, the more optimistic they are about technology opportunities, and the less they discount future generations' welfare purely because they live later. The choice of objective will also depend on judgements about political feasibility. These are decisions with such globally significant implications that they will rightly be the subject of a broad public debate at a national and international level.

The ultimate concentration of greenhouse gases anchors the trajectory for the social cost of carbon. **The social cost of carbon is likely to increase steadily over time, in line with the expected rising costs of climate-change-induced damage. Policy should therefore ensure that abatement efforts at the margin also intensify over time. But policy-makers should also spur on the development of technology that can drive down the average costs of abatement.** The social cost of carbon will be lower at any given time with sensible climate-change policies and efficient low-carbon technologies than under 'business as usual'.

Even if all emissions stopped tomorrow, the accumulated momentum behind climate change would ensure that global mean temperatures would still continue to rise over the next 30 to 50 years. Thus **adaptation is the only means to reduce the now-unavoidable costs of climate change over the next few decades. But adaptation also entails costs, and cannot cancel out all the effects of climate change**. Adaptation must go hand in hand with mitigation because, otherwise, the pace and scale of climate change will pose insurmountable barriers to the effectiveness of adaptation.

13.1 Introduction

It is important to use both science and economics to inform policies aimed at slowing and eventually bringing a stop to human-induced climate change.

Science reveals the nature of the dangers and provides the foundations for the technologies that can enable the world to avoid them. Economics offers a framework that can help policy-makers decide how much action to take, and with what policy instruments. It can also help people understand the issues and form views about both appropriate behaviour and policies. The scientific and economic framework provides a structure for the discussions necessary to get to grips with the global challenge and guidance in setting rational and consistent national and international policies.

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

Previous chapters argued that, without mitigation efforts, future economic activity would generate rising greenhouse gas emissions that would impose unacceptably high economic and social costs across the entire world. Fortunately, technology and innovation can help rein back emissions over time to bring human-induced climate change to a halt. This chapter first makes the case for strong action now, and then discusses how a shared understanding around the world of the nature of the challenge can guide that action on two fronts: mitigation and adaptation.

13.2 The need for strong and urgent action

The case for strong action can be examined in three ways: a 'bottom-up' approach, comparing estimates of the damages from unrestrained climate change with the costs of specific mitigation strategies; a 'model-based' approach taking account of interactions in the climate system and the global economy; and a 'price-based' approach, comparing the marginal costs of abatement with the social cost of carbon.

The 'bottom-up' approach was adopted in Chapters 3, 4 and 5 of this Review for the heterogeneous impacts of climate change, and in Chapters 8 and 9 for the scale and costs of possible mitigation strategies. If global temperatures continue to rise, there will be mounting risks of serious harm to economies, societies and ecosystems, mediated through many and varied changes to local climates. The impacts will be inequitable. It is not necessary to add these up formally into a single monetary aggregate to come to a judgement that human-induced climate change could ultimately be extremely costly. Chapter 7 showed that, without action, greenhouse-gas emissions will continue to grow, so these risks must be taken seriously. But Chapter 9 showed that it is possible to identify technological options for stabilising greenhouse gas concentrations in the atmosphere that would cost of around 1% of world gross world product – moderate in comparison with the high cost of potential impacts. The options considered there are not the only ways of tackling the problem, nor necessarily the best. But they do demonstrate that the problem can be tackled. And there will be valuable co-benefits, such as reductions in local air pollution.

The 'model-based' approach was illustrated in Chapter 6 for the impacts, and Chapter 10 for the costs, of mitigation. Models make it easier to consider the quantitative implications of different degrees of action and can build in some behavioural responses, both to climate change and the policy instruments used to combat it. But they do so at the cost of considerable simplification. They also require explicit decisions about the ethical framework appropriate for aggregating costs and benefits of action. The model results surveyed in this Review point in the same direction as the 'bottom up' evidence: the benefits of strong action clearly outweigh the costs.

In broad brush terms, spending somewhere in the region of 1% of gross world product on average forever could prevent the world losing the equivalent of 10% of gross world product for ever, using the approach to discounting explained in Chapters 2 and 6.

This can be thought of as akin to an investment. Putting together estimates of benefits and costs of mitigation through time, as in Figures 13.1 and 13.2, shows how incurring relatively modest net costs this century (peaking around 2050) can earn a big return later on, because of the size of the damages averted. These charts are quantitative analogues to the schematic diagram in Figure 2.4 comparing a 'business as usual' trajectory with a mitigation path. They are drawn assuming mitigation costs to be a constant 1% (Figure 13.1) and 4% (Figure 13.2) of gross world product and taking a 'business as usual' scenario with baseline climate scenario, some risk of catastrophes and a rough-and-ready estimate of non-market impacts. As explained in Chapter 6, this is now likely to underestimate the sensitivity of the climate to greenhouse gas emissions. Also, the charts focus on impacts measured in terms of how they might affect output, not wellbeing; in other words, it does not reflect the more appropriate approach to dealing with risk, as advocated in Chapter 2. But the range between the 5th and 95th percentiles of the distribution of possible impacts under the specific scenario is shown.

Figure 13.1 'Output gap' between the '550ppm C0$_2$e and 1% GWP mitigation cost' scenario and BAU scenario, mean and 5th – 95th percentile range

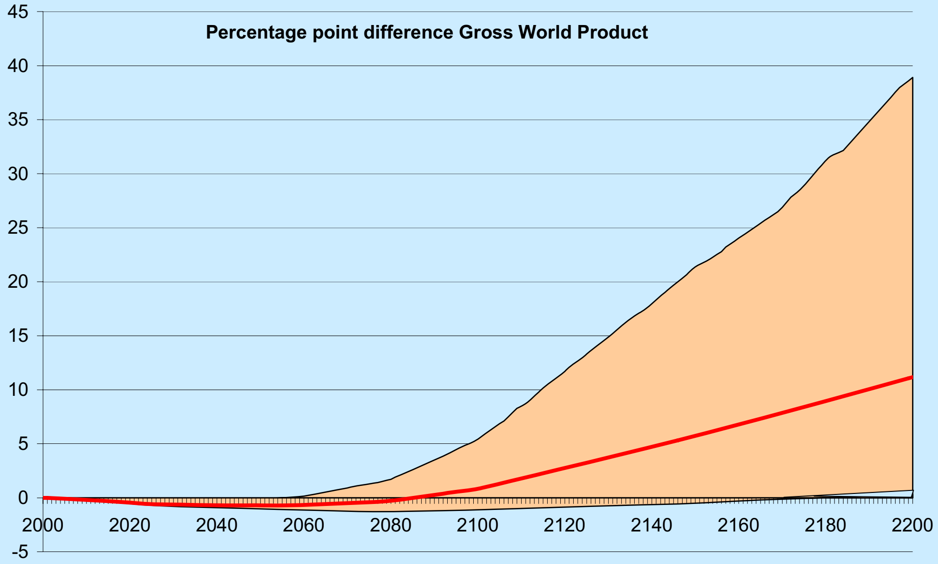
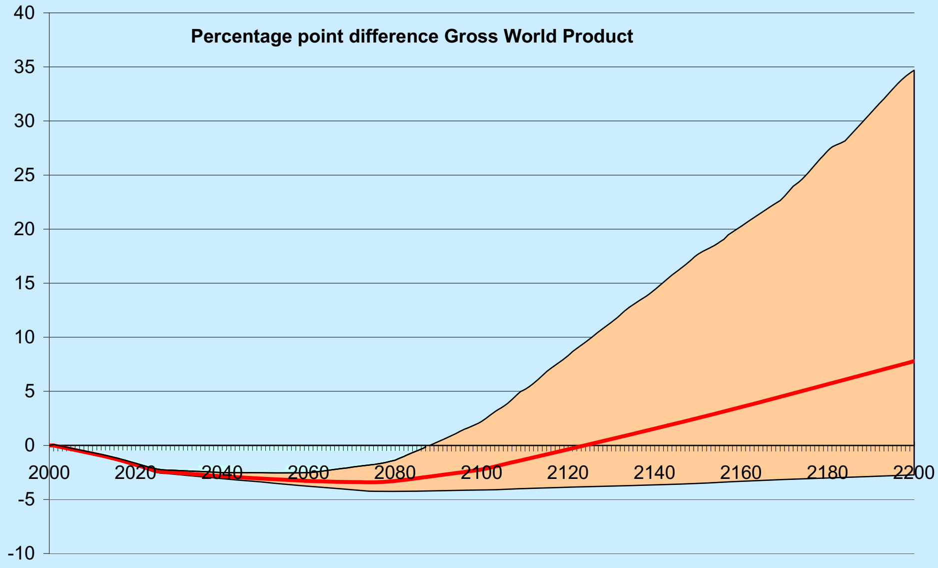


Figure 13.2 'Output gap' between the '550ppm C0$_2$e and 4% GWP mitigation cost' scenario and BAU scenario, mean and 5th – 95th percentile range



The 'price-based' approach compares the marginal cost of abatement of emissions with the 'social cost' of greenhouse gases. Consider, for example, the social cost of carbon – that is, the impact of emitting an extra unit of carbon at any particular time on the present value (at that time) of expected wellbeing or utility[1]. The extra emission adds to the stock of carbon in the atmosphere for the lifetime of the relevant gas, and hence increases radiative forcing for a long time. The size of the impact depends not only on the lifetime of the gas, but also on the size of the stock of greenhouse gases while it is in the atmosphere, and how uncertain climate-change impacts in the future are valued and discounted. The social cost of carbon has to be expressed in terms of a numeraire, such as current consumption, and is a relative price. If this price is higher than the cost, at that time, of stopping the emission of the extra unit of carbon – the marginal abatement cost – then it is worth undertaking the extra abatement, as it will generate a net benefit. In other words, if the marginal cost of abatement is lower than the marginal cost of the long-lasting damage caused by climate change, it is profitable to invest in abatement.

The ‘price-based’ approach points out that estimates of the social cost of carbon along ‘business as usual’ trajectories are much higher than the marginal abatement cost today. The academic literature provides a wide range of estimates of the social cost of carbon, spanning three orders of magnitude, from less than £0/tC (in year 2000 prices) to over £1000/tC (see Box 13.1), or equivalently from less than $0/tCO_2$ to over $400/tCO_2$. This is obviously an extremely broad range and as such makes a policy driven by pricing based on an estimate of the social cost of carbon difficult to apply. The mean value of the estimates in the studies surveyed by Tol was around $29/tCO_2$ (2000 US$), although he draws attention to many studies with a much lower figure than this.

The modelling approach that was illustrated in Chapter 6 of this Review also indicates the sensitivities of estimates of the social cost of carbon to assumptions about discounting, equity weighting and other aspects of its calculation, as described by Tol, Downing and others. Preliminary analysis of the model used in Chapter 6 points to a number around $85/tCO_2$ (year 2000 prices) for the central ‘business as usual’ case, using the PAGE2002 valuation of non-market impacts. It should be remembered that this model is different from its predecessors, in that it incorporates both explicit modelling of the role of risk, using standard approaches to the economics of risk, and makes some allowance for catastrophe risk and non-market costs, albeit in an oversimplified way. In our view, these are very important aspects of the social cost of carbon, which should indeed be included in its calculation even though they are very difficult to assess. We would therefore point to numbers for the ‘business as usual’ social cost of carbon well above (perhaps a factor of three times) the Tol mean of $29/tCO_2$ and the ‘lower central’ estimate of around $13/tCO_2$ in the recent study for DEFRA (Watkiss et al. (2005)). But they are well below the upper end of the range in the literature (by a factor of four or five). Nevertheless, we are keenly aware of the sensitivity of estimates to the assumptions that are made. Closer examination of this issue – and a narrowing of the range of estimates, if possible – is a high priority for research.

The case for strong action from the perspective of comparing the ‘business as usual’ social cost of carbon and the marginal abatement cost is powerful, even if one takes Tol’s mean or the Watkiss lower benchmark as the value of the former, when one compares it with the opportunities for low-cost reductions in emissions and, indeed, for those that make money (see Chapter 9). It is still more powerful if one takes higher numbers for the social cost of carbon, as we would suggest is appropriate, and also recognises that the SCC will increase over time, because of the current and prospective increases in the stock of greenhouse gases in the atmosphere.

All three of these approaches would lead to exactly the same estimate of the net benefits of climate-change policies and the same extent of action if models were perfect and policy-makers had full information about the world. In practice, these conditions do not hold, so the three perspectives can be used to cross-check the broad conclusions from adopting any one of them.

---

[1] The social cost of carbon and carbon price discussed here are convenient shorthand for the social cost (and corresponding price) for each individual greenhouse gas. Their relative social costs, or 'exchange rate', depend on their relative global warming potential (GWP) over a given period and when that warming potential is effective, as the latter determines the economic valuation of the damage done. Suppose there were a gas with a life in the atmosphere one tenth that of CO_2 but with ten times the GWP while it is there. The social cost of that gas today would be less than the social cost of CO_2, because it would have its effect on the world while the total stock of greenhouse gases was lower on average, so that its marginal impact would be less in economic terms.

Box 13.1 Estimates of the social cost of carbon

Downing et al (2005), in a study for DEFRA, drew the following conclusions from the review of the range of estimates of the social cost of carbon:

- The estimates span at least three orders of magnitude, from 0 to over £1000/tC (2000 £), reflecting uncertainties in climate and impacts, coverage of sectors and extremes, and choices of decision variables
- A lower benchmark of £35/tC is reasonable for a global decision context committed to reducing the threat of dangerous climate change. It includes a modest level of aversion to extreme risks, relatively low discount rates and equity weighting
- An upper benchmark for global policy contexts is more difficult to deduce from the present state of the art, but the risk of higher values for the social cost of carbon is significant.

The Downing study draws on Tol (2005), who gathered 103 estimates from 28 published studies. Tol notes that the range of estimates is strongly right-skewed: the mode was $2/tC (1995 US$), the median was $14/tC, the mean $93/tC and the 95th percentile $350/tC. He also finds that studies that used a lower discount rate, and those that used equity weighting across regions with different average incomes per head generated higher estimates and larger uncertainties. The studies did not use a standard reference scenario, but in general considered ‘business as usual’ trajectories. (See also Watkiss et al (2005) on the use of the social cost of carbon in policy-making and Clarkson and Deyes (2002) for earlier work on the social cost of carbon in a UK context.)

NB conversion rates:
£100/tC (2000 prices) = $116/tC (1995 prices) = $35.70/t$CO_2$ (2000 prices)

13.3 Setting objectives for action

Having made the case for strong action, there remains the challenge of formulating more specific objectives, so that human-induced climate change is slowed and brought to a halt without unnecessary costs. The science and economics both suggest that a shared international understanding of what the objectives of climate-change policy should be would be a valuable foundation for policy.

The problem is global. Policy-makers in different countries cannot choose their own global climate. If they differ about what they think the world needs to achieve, not only will many of them be disappointed, the distribution of efforts to reduce emissions will be inefficient and inequitable. The benefits of a shared understanding include creating consensus on the scale of the problem and a common appreciation of the size of the challenge for both mitigation and adaptation. It would provide a foundation for discussion of mutual responsibilities in tackling the challenge. At a national and individual level, it would reduce uncertainty about future policy, facilitating long-term planning and making it more likely that both adaptation and mitigation would be appropriate and cost-effective.

The ultimate objective of stopping human-induced climate change can be translated into a variety of possible long-term global goals to give guidance about the strength of measures necessary.

Table 13.1 below summarises five types of goal, each defining key stages along the causal chain from emissions to atmospheric concentrations, to global temperature changes and finally to impacts.

Table 13.1 Five types of 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 human 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 address the problem that impacts are a function of stocks not flows. -May limit 'what, where, when' flexibility and so push up costs

These different types of goal are not necessarily inconsistent, and some are more suited to particular roles than others. Public concern focuses on impacts to be avoided, and this is indeed the language of the UNFCCC, which defines the ultimate objective of the Convention as "*…to achieve…stabilisation 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, this does not provide a quantitative guide to policy-makers on the action required. The EU has defined a temperature threshold – limiting the global average temperature change to less than 2°C above pre-industrial. 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.

The analysis presented in Chapter 8, linking cumulative emissions first to long-run concentrations in the atmosphere, and then to the probabilities of different ultimate temperature outcomes, provides an alternative basis for long-term goals. It is one that allows the level of and uncertainty about both impacts and the costs of mitigation to be debated together. Once a shared understanding of what the broad objectives of policy should be has been established, it is useful to go further and translate it into terms that can guide the levels at which the instruments of policy should be set.

Any operational goal should be closely related to the ultimate impacts on wellbeing that policy seeks to avoid. But, if it is to guide policy-makers in adjusting policy sensibly over time, progress towards it must also be easy to monitor. The goal therefore should be clear, simple and specific; it must be possible to use new information regularly to assess whether recent observations of the variable targeted are consistent with hitting the goal. Policy-makers must also have some means of adjusting policy settings to alter the trajectory of the variable targeted. Seeing policy-makers adjust policy settings in this way to keep their aim on the goal would also build the credibility of climate-change policies. This is very important, if private individuals and firms are to play their full part in bringing about the necessary changes in behaviour.

A goal for atmospheric concentrations would allow policy-makers to monitor progress in a timely fashion and, if the world were going off course, adjust policy instrument settings to correct the direction of travel.

The rest of this chapter focuses on the question of what concentration of greenhouse gases in the atmosphere, measured in CO_2 equivalent, to aim for. Policy instruments should be set to make the expected long-run outcome for concentration (on the basis of today's knowledge) equal to this level. Atmospheric concentration is closer than cumulative emissions in the causal chain to the impacts with which climate-change policy is ultimately concerned. And, compared with other possible formulations of policy aspirations such as global temperature change, observations of atmospheric concentration allow more rapid feedback to policy settings[2].

Such a goal is a device to help structure and calibrate climate-change policy. But it is only a means to an end – limiting climate change – and it is useful to keep that ultimate objective in mind. Other intermediate and local goals (for example, national limits for individual countries' annual emissions or effective carbon-tax rates) may also help to move economies towards the long-run objective and to monitor the success of policy, given the long time it will take to achieve stabilisation – as long as they are consistent with, and subsidiary to, the primary goal. They may also be necessary as stepping-stones towards the adoption of a more comprehensive and coherent global objective, given the time it is likely to take to reach a shared understanding of what needs to be done. The danger is that multiple objectives may reduce the efficiency with which the main one is pursued. Part VI of the Review considers some of the problems of turning an international objective into obligations for national governments. This chapter sidesteps those problems in order to focus on what economics suggests might be desirable characteristics of the set of local, national and supranational policies that emerge from the political process.

However, the key decision now is that strong action is both urgent and necessary. That does not require immediate agreement on a precise stabilisation goal.

It is important to start taking steps in the right direction while the shared understanding is being developed.

13.4 The economics of choosing a goal for global action

Measuring and comparing the expected benefits and costs over time associated with different stabilisation levels can provide guidance to help decide how much to do and how quickly.

Estimates need to take account of the great uncertainties about climate-change damages and mitigation costs that remain even when a specific stabilisation goal is being considered. The time dimension is also important. A different stabilisation goal entails a different trajectory of emissions through time, so analysis should not simply compare the costs and benefits of extra emission reductions this year. Instead, one needs to compare incremental changes in the present values of current and future costs and benefits.

The marginal benefits of a lower stabilisation level reflect the expected impact on people's wellbeing of achieving a lower expected ultimate temperature change and a reduced risk of extreme outcomes. Risk will increase along the path towards stabilisation and cannot be accounted for simply by comparing ultimate stabilisation levels. As Chapter 2 showed, this requires judgements about how wellbeing is affected by risk, uncertainty and the distribution of the impacts of climate change across individuals and societies. Subjective assessments have to be made where objective evidence about risks is limited, particularly those associated

---

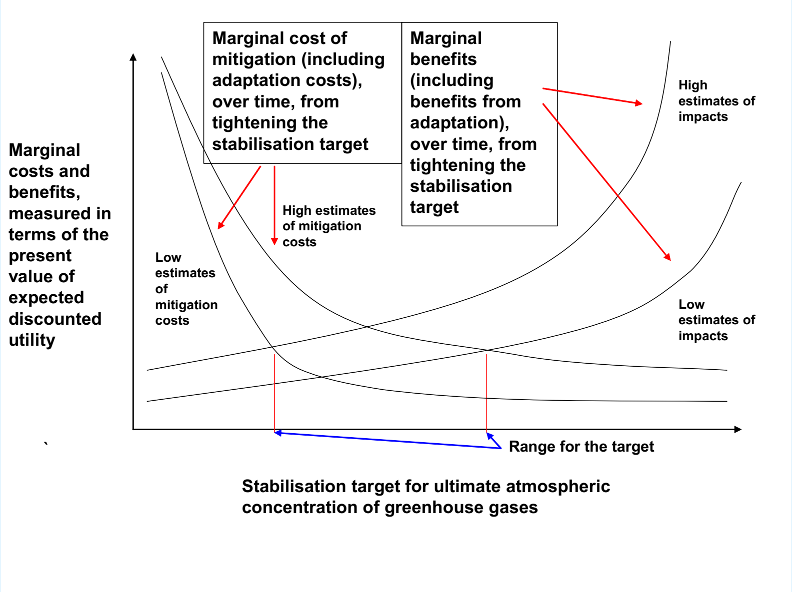
[2] Cumulative emissions are closer to the policy-induced emissions reductions that incur the *costs* of mitigating climate change. The choice between the two goals comes down to how the costs and benefits of missing the goal by some amount differ in the two cases, given uncertainty about the relationship between the two variables due to uncertainty about the functioning of carbon 'sinks', etc. This is related to the issue of whether setting greenhouse-gas prices or quotas is preferable in the face of uncertainty (see Chapter 14); the arguments there imply that, for the long run, a concentration goal is to be preferred).

with more extreme climate change. These assessments should adopt a consistent approach towards risk and uncertainty, reflecting the degree of risk aversion people decide is appropriate in this setting.

The marginal costs of aiming for a lower stabilisation level reflect the need to speed up the introduction of mitigation measures, such as development of low-carbon technologies and switching demand away from carbon-intensive goods and services. Stabilisation, however, requires emissions to be cut to below 5 $GtCO_2e$ eventually, to the Earth's natural annual absorption limit, whatever the specific GHG stock level chosen (chapter 8).

Figure 13.3 illustrates the approach sketched here. The figure shows in schematic fashion how the incremental or marginal benefits and costs of a programme of action change through time (in terms of present values) as successively lower goals are considered. As explained in Chapter 2, the benefits (and the costs) of action should be thought of in terms of the expected impacts on wellbeing over time, appropriately discounted, not simply monetary amounts. That allows for risk weighting, risk aversion and considerations of fairness across individuals and generations to be incorporated in the analysis. For simplicity, two 'marginal benefits' curves are drawn to remind the reader of the huge uncertainties. In practice, people differ about the weights they attach to different sorts of climate-change impacts. There is scope for legitimate debate about how they should be aggregated to compare them with the costs of mitigation.

Figure 13.3 Schematic representation of how to select a stabilisation level



The costs of mitigation, too, should be thought of in terms of their impact on broad measures of wellbeing. It matters on whom the costs fall, when they are incurred and what the uncertainties about them are. Figure 13.2 shows two curves, for high and low estimates of the incremental costs of tougher action to curb emissions. They are drawn with the costs rising more sharply as the stabilisation level considered becomes lower and lower. The ideal objective is where the marginal benefits of tougher action equal the marginal costs. Given the uncertainty about both sides of the ledger, this approach cannot pin down a precise number but can, as the chart indicates, suggest a range in which it should lie. The range excludes levels where either the incremental costs of mitigation or the incremental climate-change impacts are rising very rapidly.

Uncertainty is an argument for setting a more demanding long-term policy, not less, because of the asymmetry between unexpectedly fortunate outcomes and unexpectedly bad ones.

Suppose 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 up the probability distribution, the consequences for global wellbeing become worse. But, more than that, the consequences are 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 wellbeing[3].

There is a second line of reasoning linking uncertainty with stronger action. There is an asymmetry due to the very great difficulty of reducing the atmospheric concentration of greenhouse gases. Increases are irreversible in the short to medium run (and very difficult even in the ultra-long run, on our current understanding). If new information is collected that implies that climate-change impacts are likely to be *worse* than we now think, we cannot 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[4]. There is also an option value associated with delaying investment in long-lived structures, plant and equipment for greenhouse gas abatement. 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.

Some of the parameters that modellers have treated as uncertain, such as discount factors and equity weights, reflect societies' preferences. In the process of agreeing an international stabilisation objective, or at least narrowing its range, discussions have to resolve, or at least reduce disagreement over, the issues of social choice lying behind these uncertainties.

As explained in Chapter 2 and its appendix, this Review argues for using a low rate of pure time preference and assuming a declining marginal utility of consumption as consumption increases across time, people and states of nature. However, the magnitude of the risks described in Part II of this Review suggests that a broad range of perspectives on these two issues indicates the need for strong action to mitigate emissions.

Given this framework, the evidence on the costs and benefits of mitigation reviewed in the chapters above can give a good indication of upper and lower limits that might be set for the extent of action, as argued below. The policy debate should seek some indication of where within these limits international collective action should aim[5]. But it is vital that, while a shared understanding permitting agreement on a common goal is being developed, initial actions to reduce emissions are not delayed.

There is room for debate about precisely how fast emissions need to be brought down, but not about the direction in which the world now has to move.

13.5 Climate-change impacts and the stabilisation level

Expected climate-change impacts rise with the atmospheric concentration of greenhouse gases, because the probability distributions for the long-run global temperature move upwards. The evidence strongly suggests that 550ppm CO_2e would be a dangerous place to be, with substantial risks of very unpleasant outcomes.

Figure 13.3 illustrates how the risk of various impacts occurring is associated with different stabilisation levels[6] (see also Box 8.1 for frequency distributions of the range of temperature increases associated with various stabilisation levels in a selection of climate models). The top section shows the 5 – 95% probability ranges of temperature increases projected at different stabilisation levels; the central marker is the 50th percentile point. The bottom section

---

[3] More formally, we take impacts to be convex in atmospheric concentration and note that the expected utility of a range of outcomes is lower than the utility of the expected outcome, if marginal utility declines with income. This is discussed further in Chapter 2.

[4] See, for example, Kolstad (1996), Pindyck (2000) and Ingham and Ulph (2005)

[5] If policy-makers adopt a zone rather than a single number as a goal, recognising that no policy is able to ensure that a point goal can be hit precisely, it should be within these upper and lower limits. It would also be desirable if the zone were considerably narrower than the span of those limits, so as not to weaken substantially the discipline on policy-makers to adjust policy settings if it looks as if the goal is not going to be met. Too wide a target zone also increases the risk of different policy-makers around the world choosing policy settings that are inconsistent with each other.

[6] Where the risk is defined using subjective probabilities based on current knowledge of climate sensitivity – the relationship between greenhouse gas concentration and temperatures.

shows the projected impacts. At some point, the risks of experiencing some extremely damaging phenomena begin to become significant. Such phenomena include:

- Irreversible losses of ecosystems and extinction of a significant fraction of species.
- Deaths of hundreds of millions of people (due to food and water shortages, disease or extreme weather events).
- Social upheaval, large-scale conflict and population movements, possibly triggered by severe declines in food production and water supplies (globally or over large vulnerable areas), massive coastal inundation (due to collapse of ice sheets) and extreme weather events.
- Major, irreversible changes to the Earth system, such as collapse of the Atlantic thermohaline circulation and acceleration of climate change due to carbon-cycle feedbacks (such as weakening carbon absorption and higher methane releases) – at high temperatures, stabilisation may prove more difficult, or impossible, because such feedbacks may take the world past irreversible tipping points (chapter 8).

The expected impacts of climate change on well-being in the broadest sense are likely to accelerate as the stock of greenhouse gases increases, as argued in Chapter 3. The expected benefits of extra mitigation will therefore increase with the stabilisation level[7]. In Figure 13.2, the marginal benefit curve is therefore drawn as rising increasingly steeply with the stabilisation level. There are four main reasons:

- As global mean temperatures increase, several specific climate impacts are likely to increase more and more rapidly: in other words, the relationship is convex. Examples include the relationship between windstorm wind-speed and the value of damage to buildings (IAG (2005)) and new estimates of the relationship between temperature and crop yields (Schlenker and Roberts (2006));
- Different elements of the climate system may interact in such a way that the combined impacts rise more and more rapidly with temperature;
- As global mean temperatures increase several degrees above pre-industrial levels, existing stresses would be more and more likely to trigger the most severe impacts of climate change that arise from interactions with societies, namely social upheaval, large-scale conflict and population movements;
- As global mean temperatures increase, so does the risk that positive feedbacks in the climate system, such as permafrost melting and weakening carbon sinks, kick in.

The uncertainties about impacts make it impossible to quantify exactly where the marginal impacts of climate change will rise more sharply. However, across the current body of evidence, two approximate global turning points appear to exist, at around 2 – 3°C and 4 – 5°C above pre-industrial:

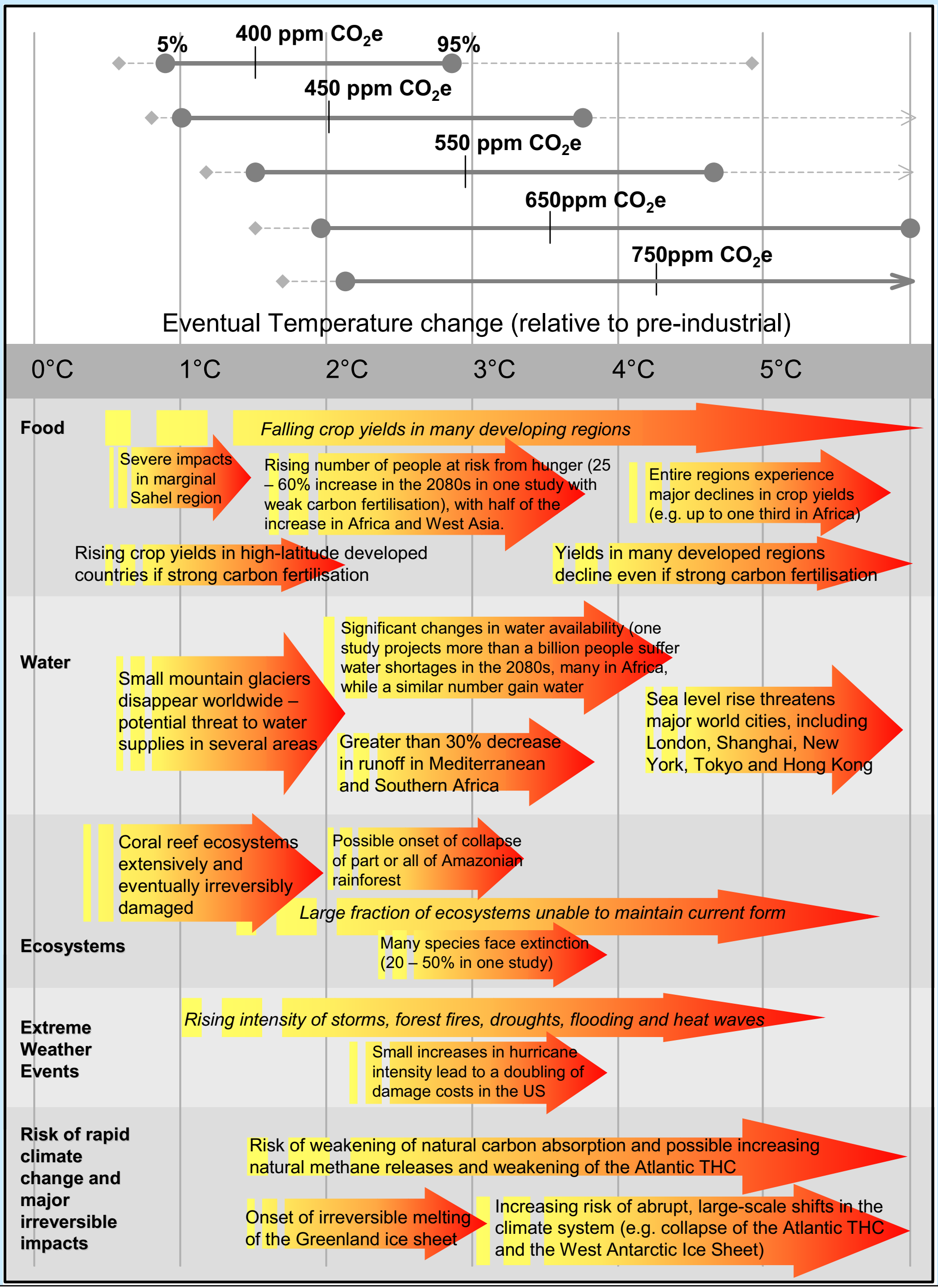
- At roughly 2 – 3°C above pre-industrial, a significant fraction of species would exceed their adaptive capacity and, therefore, rates of extinction would rise. This level is associated with a sharp decline in crop yields in developing counties (and possibly developed counties) and some of the first major changes in natural systems, such as some tropical forests becoming unsustainable, irreversible melting of the Greenland ice sheet and significant changes to the global carbon cycle (accelerating the accumulation of greenhouse gases).
- At around 4 – 5°C above pre-industrial, the risk of major abrupt changes in the climate system would increase markedly. At this level, global food production would be likely to fall significantly (even under optimistic assumptions), as crop yields fell in developed countries.

---

[7] There is, however, considerable uncertainty about how climate-change effects will evolve as temperatures rise, as many of the hypothesised effects are expected to take place or intensify outside the temperature range experienced by humankind, and so cannot be verified by empirical observation. One characteristic of the climate physics works in the opposite direction: the expected rise in temperature is a function of the *proportional* increase in the stock of greenhouse gases, not its *absolute* increase. As a result, some integrated assessment models, for example Nordhaus' DICE model, have S-shaped functions to represent the costs of climate-change impacts.

Figure 13.4 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 higher greenhouse gas levels. 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 TAR 2001 (Wigley and Raper (2001)) and a recent Hadley Centre ensemble study (Murphy et al. (2004)). The vertical line indicates the mean of the 50th percentile point. The dashed lines show the 5 – 95% range based on eleven recent studies (Meinshausen (2006)). 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 3.2). This figure shows potential changes based on current scientific literature.



Few studies have examined explicitly the benefits of choosing a lower stabilisation level. Generally, those that have done so show that the benefits vary across sectors. For example, in reducing the stabilisation temperature from 3.5°C to 2.5°C, significant benefits to ecosystems and in the number of people exposed to water stress have been estimated[8].

---

[8] Arnell et al. (2004)

However, such evidence is strongly model-dependent and, therefore, subject to significant uncertainties.

Recent integrated assessment models (discussed in Chapter 6) have attempted to capture some of these uncertainties by representing damage functions stochastically. These cover several dimensions, including the risk of major abrupt changes in the climate systems (they do not, however, generally include estimates of the potential costs of social disruption). They also take account of adaptation to climate change to varying extents. Chapter 6 notes that such models show a steep increase in marginal costs with rising temperature. The PAGE2002 model, used in chapter 6, has the advantage of allowing for the uncertainty in the literature about several dimensions of impacts. It permits a comparison of the probability distribution of projected gross world product net of the cost of climate change with the hypothetical gross world product without climate change, for a given increase in global mean temperature, thus providing an estimate of climate-change costs (see Table 13.2, where estimates include some measure of 'non-market' impacts). The costs of climate change as a proportion of gross world product are modelled as an uncertain function of the increase in temperature, among other factors.

Table 13.2 Estimates of the costs of climate change by temperature increase, as a proportion of gross world product, from PAGE2002

	Mean expected cost	5th percentile	95th percentile
2°C	0.6%	0.2%	4.0%
3°C	1.4%	0.3%	9.1%
4°C	2.6%	0.4%	15.5%
5°C	4.5%	0.6%	23.3%

Source: Hope (2003)

Thus, for example, according to PAGE2002, if the temperature increase rises from 2ºC to 3ºC, the mean damage estimate increases from 0.6% to 1.4% of gross world product; but the 'worst case' – the 95th percentile of the probability distribution – goes from 4.0% to 9.1%. These costs fall disproportionately on low-latitude, low-income regions, but there are significant net costs in higher-latitude regions, too.

The estimates of the costs of impacts suggest that the mean expected damages rise significantly if the global temperature change rises from 3ºC to 4ºC and even more from 4ºC to 5ºC. But the damages associated with a 'worst case' scenario – the 95th percentile of the distribution – rise more rapidly still.

On the basis of current scientific understanding, it is no longer possible to prevent all risk of dangerous climate change.

Box 8.1 showed how the risk of exceeding these temperature thresholds rises at stabilisation levels of 450, 550, 650, and 750ppm CO_2e. This box implies:

- Even if the world were able to stabilise at current concentrations, it is already possible that the ultimate global average temperature increase will exceed 2°C
- At 450ppm CO_2e, there is already a 18% chance of exceeding 3°C, according to the Hadley ensemble reported in the table, but a very high chance of staying below 4°C
- By 550ppm CO_2e, there is a 24% chance that temperatures will exceed 4°C, but less than a 10% chance that temperatures will exceed 5°C.

It can be seen that a move above 550ppm CO_2e would entail considerable additional costs of climate change, taking into account the further increases in the risks of extreme outcomes.

Our work with the PAGE model suggests that, allowing for uncertainty, if the world stabilises at 550ppm CO_2e, climate change impacts could have an effect equivalent to reducing consumption today and forever by about 1.1%[9]. As Chapter 6 showed, this compares with around 11% in the corresponding 'business as usual' case – ten times as high. With stabilisation at 450ppm CO_2e, the percentage loss would be reduced to 0.6%, so choosing the tougher goal 'buys' about 0.5% of consumption now and forever. Choosing 550ppm instead of 650ppm CO_2e 'buys' about 0.6%. As with all models, these numbers reflect heroic

---

[9] These figures are based on the 'broad impacts, standard climate sensitivity' case among the scenarios considered in Chapter 6. As such, they do not allow for equity weighting; if they did, the estimates in the text would be higher. They would also be higher if higher estimates of climate sensitivity, incorporating more amplifying feedback mechanisms, were used. The valuation of non-market impacts is particularly difficult and dependent on ethical judgements, as explained in Chapter 6.

assumptions about the valuation of potential impacts, although, as Chapter 6 explains, they reflect an attempt to ensure the model calibration reflects the nature of the problem faced. They also entail explicit judgements about some of the ethical issues involved. In addition, the PAGE2002 model is not ideal for analysing stabilisation trajectories. Nevertheless, all integrated assessment models are sensitive to the assumptions and they should be taken as only indicative of the quantitative impacts, given those assumptions. It should be noted that the results quoted from Chapter 6 leave out much that is important, and the other models referred to there leave out more.

13.6 The costs of mitigation and the stabilisation level

The lower the stabilisation level chosen, the faster the technological changes necessary to bring about a low-carbon society will have to be implemented.

Stabilising close to the current level of greenhouse gas concentration would require implausibly rapid reductions in emissions, because the technologies currently available to achieve such reductions are still very expensive[10] and the appropriate structures, plant and equipment are not yet in place. Hitting 450ppm CO_2e, for example, appears very difficult to achieve with the current and foreseeable technologies, as suggested in Chapter 8. It would require an early peak in emissions, very rapid emission cuts (more than 5% per year), and reductions by 2030 of around 70%. Even with such cuts, the stock of greenhouse gases covered by the Kyoto Protocol would initially overshoot, their effect temporarily masked by aerosols (so that there would be only a very small overshoot in radiative forcing)[11]. Costs would start to rise very rapidly if emissions had to be reduced sharply before the existing capital stock in emissions-producing industries would otherwise be replaced and at a speed that made structural adjustments in economies very abrupt and hence expensive. Abrupt changes to economies can themselves trigger wider impacts, such as social instability, that are not covered in economic models of the costs of mitigation.

Technological change eventually has to get annual emissions down to their long-run sustainable levels without having to accelerate sharply the retirement of the existing capital stock, if costs are to be contained. Model-based estimates of the present value of the costs of setting a tougher stabilisation objective are not widely available in the literature. That reflects, among other factors, the unavoidable uncertainties about the pace and costs of future innovation. In principle, such estimates ought to reflect the incidence of the mitigation costs, which ultimately fall on the consumers of currently GHG-intensive goods and services, as well as their monetary value (just as the incidence of climate-change impacts matters as well as their level), but there has been little investigation of this aspect of the problem.

However, there are some estimates to help as a guide. Chapter 9 in effect argued that the extra mitigation costs incurred by stabilising at around 550ppm CO_2e instead of allowing business to continue as usual would probably be of the order of 1% of gross world product. Choosing a lower goal would cost more, a higher goal less. Some studies of costs give more of an indication of their sensitivity to the stabilisation objective. For example, the study by Edenhofer et al (2006), averaging over five models, provides the following estimates of cost increases from choosing a lower stabilisation goal:

Table 13.3 Some model-based estimates of the increase in mitigation costs from reducing a stabilisation goal (discounted percentage of gross world output), by discount rate used

	5% pa	'Green Book'	2% pa	1% pa	0% pa
Moving from 500ppm to 450ppm CO_2	0.25%	0.39%	0.43%	0.51%	0.58%
Moving from 550ppm to 500ppm CO_2	0.06%	0.11%	0.12%	0.14%	0.18%

Source: adapted from Edenhofer et al. (2006); 'Green Book' is a declining discount rate over time, as in HM Treasury Green Book project-appraisal guidance.

---

[10] Costs of delivering any particular level of abatement are likely to decline with investment and experience; see Chapters 9 and 16.

[11] The world is already at around 430ppm CO_2e if only the greenhouse gases covered by the Kyoto Protocol are included; but aerosols reduce current radiative forcing. The projection reported in the text assumes that the aerosol affect diminishes over time, but for a period counteracts a temporary rise in Kyoto greenhouse gases above 450ppm CO_2e. As the concentration of greenhouse gases is rising at around 2.5 ppm CO_2e per year, and annual emissions are increasing, 450ppm CO_2e could be reached in less than ten years.

It is important to note that these results are tentative, and that there is still much debate about the role of induced technological progress, the focus of the study. Nevertheless, the bottom line in Table 13.3 suggests that the extra mitigation costs from choosing a goal of around 500ppm instead of 550ppm CO_2 would be small, ranging from 0.06% to 0.18% of gross world output, depending on how much future costs are discounted. In terms of a CO_2e goal, this is similar to going from 600 – 700ppm to 550 – 650ppm, depending on what happens to non-CO_2 greenhouse gases (see Chapter 8). The extra costs of choosing a goal of 450ppm CO_2 instead of 500ppm CO_2 would be higher, ranging from 0.25% to 0.58%; this is similar to going from 550 – 650ppm CO_2e to 500 – 550ppm CO_2e. None of the discount schemes used are the same as the one used in Chapter 6 of this Review, as the discount rates are not path-dependent. However, as stabilisation reduces the chances of very bad outcomes compared with ‘business as usual’, the discounting issue is less important than when evaluating potential impacts without mitigation. It is important to note that the studies concerned take the year 2000 as a baseline. Given the probable cumulative emissions since then, the goals would now be more difficult and expensive to hit.

The recent US Climate Change Science Program draft report on scenarios of greenhouse gas emissions and atmospheric concentrations also provides useful estimates, reporting for various points in time the percentage change in gross world product expected due to adopting policies to meet four different stabilisation goals[12]. Again, the studies covered take 2000 as the base year. The implications for incremental costs (as a fraction of gross world output) of adopting successively tougher goals are summarised in Table 13.4 below. These studies were not designed with the objective of this chapter in mind, of course, and the draft is subject to revision, so the estimates should be regarded as suggestive of magnitudes, not definitive.

Table 13.4 Some model-based estimates of the incremental savings in mitigation costs from relaxing a stabilisation goal (% of gross world output in the relevant year)

Incremental change	Model	2020	2040	2060	2080	2100
Moving from around 550ppm to around 450ppm CO_2 (670ppm to 525ppm CO_2e)	IGSM	1.6%	2.9%	4.4%	6.2%	9.3%
	MERGE	0.7%	1.3%	1.5%	1.2%	0.7%
	MiniCAM	0.2%	0.6%	1.0%	0.8%	0.6%
Moving from around 650ppm to around 550ppm CO_2 (820ppm to 670ppm CO_2e)	IGSM	0.3%	0.8%	1.4%	2.1%	3.7%
	MERGE	0.0%	0.1%	0.3%	0.4%	0.5%
	MiniCAM	0.0%	0.1%	0.3%	0.4%	0.3%
Moving from around 750ppm to 650ppm CO_2 (970ppm to 820ppm CO_2e)	IGSM	0.1%	0.2%	0.5%	0.9%	1.4%
	MERGE	0.0%	0.0%	0.1%	0.1%	0.1%
	MiniCAM	0.0%	0.0%	0.0%	0.1%	0.3%

Source: Adapted from US CCSP Synthesis and Assessment Product 2.1, Part A: Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations, Draft for public comment, June 26, 2006[13]

Table 13.4 shows in the bottom panel that the extra costs incurred by adopting an objective of around 820ppm instead of 970ppm CO_2e are very small, and, for two of the three models (MERGE and MiniCAM in the middle panel), aiming for around 670ppm instead of 820ppm CO_2e also costs little. According to the same two models, choosing 525ppm instead of 670ppm CO_2e increases costs by around 1% of gross world product, the amount varying somewhat over time. The most pessimistic model here generates considerably higher

---

[12] US CCSP Synthesis and Assessment Product 2.1, Part A: Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations, Draft for public comment, June 26, 2006.

[13] The ranges in terms of CO_2e are derived from the long-run constraints on total radiative forcing in the modelling exercise.

estimates for the total yearly costs of mitigation, reflecting its relatively high trajectory for ‘business as usual’ emissions and relatively pessimistic assumptions about the likely pace of innovation in low-carbon technologies. The studies suggest that mitigation costs start to rise sharply towards the bottom of the ranges of stabilisation levels considered.

Delay will make it more difficult and more expensive to stabilise at or below 550ppm CO_2e.

All of these studies take as a starting point the year 2000. If it takes 20 years or so before strong policies are put in place globally, it is likely that the world would already be at somewhere around 500ppm CO_2e, making it very difficult and expensive then to take action to stabilise at around 550ppm.

13.7 A range for the stabilisation objective

Integrated assessment models have been used in a number of studies to compare the marginal costs and marginal benefits of climate-change policy over time. But many of the estimates in the literature do not take into account the latest science or treat risk and uncertainty appropriately. Doing so would bring down the stabilisation level desired.

In some cases, the models have been used to estimate the ‘optimal’ amount of mitigation that maximises benefits less costs. These studies recommend that greenhouse gas emissions be reduced below business-as-usual forecasts, but the reductions suggested have been modest. For example, on the basis of the climate sensitivities and assessments available at the time the studies were undertaken,

- Nordhaus and Boyer (1999) found that the optimal global mitigation effort reduces atmospheric concentrations of carbon dioxide from 557ppm in 2100 (business-as-usual) to 538ppm. This reduces the global mean temperature from an estimated 2.42°C above 1900 levels to 2.33°C;
- Tol (1997) found that the optimal mitigation effort reduces the global mean temperature in 2100 from around 4°C above 1990 levels to between around 3.6°C and 3.9°C, depending on whether countries cooperate and on the costs of mitigation;
- Manne et al. (1995) did not use their model to find the optimal reduction in emissions, but the policy option they explored that delivers the highest net benefits reduces atmospheric concentrations of carbon dioxide from around 800ppm in 2100 to around 750ppm, reducing global mean temperature from around 3.25°C above 1990 levels to around 3°C.

However, the optimal amount of mitigation may in fact be greater than these studies have suggested. Above all, they carry out cost-benefit analysis appropriate for the appraisal of small projects, but we have argued in Chapter 2 that this method is not suitable for the appraisal of global climate change policy, because of the very large uncertainties faced. As a result, these studies underestimate the risks associated with large amounts of warming. Neither does any of these studies place much weight on benefits and costs accruing to future generations, as a consequence of their ethical choices about how to discount future consumption. Manne et al. apply a much higher discount rate to utility than do we in Chapter 6. Nordhaus and Boyer assume relatively low and slowing economic growth in the future, which reduces future warming. Tol estimates relatively modest costs of climate change, even at global mean temperatures 5-6°C above pre-industrial levels. Recent scientific developments have placed more emphasis on the dangers of amplifying feedbacks of global temperature increases and the risks of crossing irreversible tipping points than these models have embodied.

Given the paucity of estimates of the appropriate stabilisation level and the disadvantages of the ones that exist, this chapter does not propose a specific numerical goal. Instead, it explores how economic analysis can at least help suggest upper and lower limits to the range for an atmospheric concentration goal. Allowing for the current uncertainties, the evidence suggests that the upper limit to the stabilisation range should not be above 550ppm CO_2e.

Putting together our results on the valuation of climate-change impacts with the mitigation-cost studies suggests that the benefits of choosing a lower stabilisation goal clearly outweigh the costs until one reaches 550 – 600ppm CO_2e. But around this level the cost-benefit calculus starts to get less clear-cut. The incremental mitigation costs of choosing 500 – 550ppm instead of 550 – 600ppm CO_2e are three to four times as much as the incremental costs of choosing 550 – 600ppm instead of 600 – 650ppm CO_2e, according to the numbers in Edenhofer et al. The higher mitigation costs incurred if 500 – 550ppm is chosen instead of 550 – 600ppm CO_2e might be of similar size to the incremental benefits. They would be bigger if induced technological change were inadequate or 'business as usual' emissions were at the higher end of projections, as in the IGSM projections reported in Table 13.4.

As far as the climate-change impacts are concerned, the incremental benefits might be bigger than these calculations allow – for example, if policy-makers are more risk-averse than the PAGE calculations assumed or attach more weight to non-market impacts. Nevertheless, in choosing an upper limit to the stabilisation range, one needs to consider what is appropriate if climate-change impacts turn out to be towards the low end of their probability distribution (for a given atmospheric concentration) and mitigation costs towards the high end of their distribution. Following broadly this approach, but assuming mitigation costs are brought down over time by induced technological change, we suggest an upper limit of 550ppm CO_2e.

The lower limit to the stabilisation range is determined by the level at which further tightening of the goal becomes prohibitively expensive. On the basis of current evidence, stabilisation at 450ppm CO_2e or below is likely to be very difficult and costly.

Cost estimates derived from modelling exercises suggest that costs as a share of gross world product would increase sharply if a very ambitious goal were adopted (see Chapter 10). It is instructive that cost modelling exercises rarely consider stabilisation below 500ppm CO_2e. Edenhofer et al point out that some of the models in their study simply cannot find a way of achieving 450ppm CO_2e. Even stabilising at 550ppm CO_2e would require complete transformation of the power sector. 450ppm CO_2e would in addition require very large and early reductions of emissions from transport, for which technologies are further away from deployment. Given that atmospheric greenhouse gas levels are now at 430ppm CO_2e, increasing at around 2.5ppm/yr, the feasibility of hitting 450ppm CO_2e without overshooting is very much in doubt. And it would be unwise to assume that any overshoot could be clawed back.

The evidence on the benefits and costs of mitigation at different atmospheric concentrations in our view suggests that the stabilisation goal should lie within the range 450 – 550ppm CO_2e.

The longer action is delayed, the higher will be the lowest stabilisation level achievable. The suggested range reflects in particular the judgements that:

- Any assessment of the costs of climate change must take into account uncertainty about impacts and allow for risk aversion. Because of the risk of very adverse impacts, extreme events and amplifying feedbacks, this implies adopting a tougher goal than if uncertainty were ignored
- Proper weight should be given to the interests of future generations. Future individuals should be given the same weight in ethical calculations as those currently alive, if it is certain that they will exist. But, as there is uncertainty about the existence of future generations, it is appropriate to apply some rate of discounting over time. That points to the use of a positive, but small, rate of pure time preference (see Chapter 2 and its appendix)
- Proper attention should be paid to the distribution of climate-change impacts, in particular to the disproportionate impact on poor people
- Productivity growth in low-greenhouse-gas activities will speed up if there is more output from and investment in these activities
- The speed of decarbonisation is constrained by the current state of technology and the availability of resources for investment in low-carbon structures, plant, equipment and processes.

It is clear that studies of climate-change impacts and of mitigation costs do not yet establish a narrow range for the level at which the atmospheric concentrations of greenhouse gases should be stabilised. More research is needed to narrow the range further. There will always be disagreements about the size of the risks being run, the appropriate policy stance towards risk, and the valuation of social, economic and ecological impacts into the far future. But the range suggested here provides room for negotiation and debate about these. And we would argue that agreement on the range stated does not require signing up to all of the judgements specified above. In presenting the arguments, for example, we have omitted a number of important factors that are likely to point to still higher costs of climate change and thus still higher benefits of lower emissions and a lower stabilisation goal.

In any case, agreement requires discussion and negotiation about the ethical issues involved. Chapter 6 demonstrates that taking proper account of the non-marginal nature of the risks from climate change leads to a higher estimate of risk-adjusted losses of wellbeing than if the larger risks are ignored or submerged in simple averages. Those who weigh more heavily the potential costs of the climate change possible at any given stabilisation level will argue for a goal towards the lower end of the range. Greater risk aversion and more concern for equity across regions and generations will push in the same direction. But those who are pessimistic about the direction and pace of technological developments or who believe emissions under 'business as usual' will grow more rapidly than generally expected will tend to advocate a goal towards the upper limit, other things being equal.

The EU has adopted an objective, endorsed by a large number of NGOs and policy think-tanks, to limit global average temperature change to less than 2°C relative to pre-industrial levels. This goal is based on a precautionary approach. A peak temperature increase of less than 2°C would strongly reduce the risks of climate-change impacts, and might be sufficient to avoid certain thresholds for major irreversible change – including the melting of ice-sheets, the loss of major rainforests, and the point at which the natural vegetation becomes a source of emissions rather than a sink. Some would argue that the implications of exceeding the 2°C limit are sufficiently severe to justify action at any cost. Others have criticised the 2°C limit as arbitrary, and have raised questions about the feasibility of the action that is required to maintain a high degree of confidence of staying below this level. Recent research on the uncertainties surrounding temperature projections suggests that at 450ppm CO_2e there would already be a more-than-evens chance of exceeding 2°C (see Chapter 8). This highlights the need for urgent action and the importance of keeping quantitative objectives under review, so that they can be updated to reflect the latest scientific and economic analysis.

Some of the uncertainties will be resolved by continuing progress in the science of climate change, but ethics and social values will always have a crucial part to play in decision-making. The precise choice of policy objective will depend on values, attitudes to risk and judgements about the political feasibility of the objective. It is a decision with significant implications that will rightly be the subject of a broad public and international debate.

13.8 Implications for emissions reductions and atmospheric concentrations

Stabilisation of atmospheric concentration implies that annual greenhouse-gas emissions must peak and then fall, eventually reaching the level that the Earth system can absorb annually, which is likely to be below 5 GtCO$_2$e.

At the moment, annual emissions are over 40 GtCO$_2$e. Chapter 8 showed how, for the range of stabilisation levels considered here, annual emissions should start falling within the next 20 years, if implausibly high reduction rates are to be avoided later on. Global emissions will have to be between 25% and 75% lower than current levels by 2050. That illustrates the fact that, even at the high end of the stabilisation range, major changes in energy systems and land use are required within the next 50 years.

While annual emissions are likely to rise first and then fall, atmospheric concentrations are likely to continue to rise until the long-term objective is reached.

For any given stabilisation level, overshooting entails increased risks of climate change, by increasing the chances of triggering extreme events associated with higher concentration levels than the goal, and amplifying feedbacks on concentration levels. The expected impacts on wellbeing associated with any stabilisation level are thus likely to be smaller if overshooting is avoided. As reducing emissions in agriculture appears relatively difficult, and that sector accounts for more than 5 GtCO$_2$e per year by itself already, stabilisation is likely ultimately (well beyond 2050) to require complete decarbonisation of all other activities and some net sequestration of carbon from the atmosphere (e.g. by growing and burning biofuels, and capturing and storing the resultant carbon emissions, or by afforestation). Overshooting and return require that annual emissions can at some stage be reduced for a period below the level consistent with a stable level of the stock of greenhouse gases. On the basis of the current economic and technological outlook, that is likely to be very difficult.

Setting up a long-run stabilisation goal does not, however, preclude future revisions to make it more ambitious, if either technological progress is more far-reaching than anticipated or the expected impacts of rises in concentration levels rise. But, equally, unexpected difficulties in driving technical progress or a downward revision in expected impacts of climate change would warrant a less challenging goal. Given the pervasive uncertainties about both costs and benefits of climate-change policies, it is essential that any policy regime incorporate from the outset mechanisms to update the long-run goal in a transparent fashion in response to new developments in the science or economics.

The precise trajectory of annual emissions will depend on, among other factors, how climate-change policy is implemented, the pace of economic growth and the extent of innovation, particularly in the energy sector. Chapter 9 demonstrated that mitigation is more likely to be carried out cost effectively if policy encourages 'what, where and when' flexibility, so setting a precise trajectory as a firm intermediate objective is likely to be unnecessarily costly. Trajectories can nevertheless give a guide as to whether emissions are on course to reach the long-term goal.

13.9 The social cost of carbon

Calculations of the social cost of carbon have commonly been used to show the price that the world has to pay, if no action is taken on climate change, for each tonne of gas emitted – as in Section 13.2. But the concept can also be used to evaluate the damages along a stabilisation trajectory[14].

Choosing a concentration level to aim for also anchors a trajectory for the social cost of carbon. Without having a specific stabilisation goal in mind, it is difficult to calibrate what the carbon price should be – or, more generally, how strong action should be. The social cost of carbon will be lower at any given time with sensible climate-change policies than under 'business as usual'.

The social cost of carbon will be lower, the lower the ultimate stabilisation level. The social cost of carbon depends on the overall strategy for mitigating climate change and can help support that strategy, for instance by helping to evaluate abatement proposals. But it should not be seen as the driver of strategy. If the ultimate stabilisation goal has been chosen sensibly, the social cost of carbon along the stabilisation trajectory should be a good guide to the carbon price needed to help persuade firms to make the carbon-saving investments and undertake the research and development that would help deliver the necessary changes and entice consumers to buy fewer GHG-intensive goods and services. However, as Part IV of this Review argues, carbon pricing is only part of what needs to be done to bring down emissions.

If the concentration of carbon in the atmosphere rises steadily towards its long-run stabilisation level (so there is no overshooting), and expected climate-change damages accelerate with concentrations, the social cost of carbon will rise steadily over time, too[15]. An extra unit of carbon will do more damage at the margin the later it is emitted, because it will be around in the atmosphere while concentrations are higher, and higher concentrations mean larger climate-change impacts at the margin[16].

The social cost of carbon will be lower at any given time with sensible climate-change policies than under 'business as usual', because concentrations will be lower at all points in time. Hence, *for given assumptions about discounting and the other relevant factors*, the social cost of carbon associated with sensible emissions strategies is likely to be considerably lower than

---

[14] The social cost of carbon is well defined along any specific emissions trajectory, not only stabilisation trajectories, as the usual calculations of 'business as usual' SCCs illustrate.

[15] This requires that the convexity of the relationship between expected damages (in terms of broad measures of wellbeing) and global mean temperature increases outweighs the declining marginal impact of increases in concentration on temperature as concentration rises

[16] The social cost of carbon can also be thought of as the shadow price of carbon if there are no other distortions in the economy, apart from the greenhouse-gas externality, affected by emissions. The shadow-price path over time will depend on the precise dynamics of expected growth, climate-change impacts, the rate of removal of CO_2 from the atmosphere, discount rates and the marginal utility of income. The social cost of carbon is likely to rise faster, the higher is expected economic growth, the higher the rate at which total impacts rise with concentrations, the higher the decay rate of the greenhouse gases, and the higher the pure rate of time preference.

estimates reviewed in the recent DEFRA study, which were based on various ‘business as usual’ scenarios[17].

The social cost of carbon will also be lower if the efficiency of emissions-abatement methods improves rapidly and new low-carbon technologies prove to be cheap and easy to spread around the world. In that case, it would be worthwhile undertaking more mitigation and a lower stabilisation level would be appropriate. The lower stabilisation level and path drive down the SCC – better technology is a means to that end. Policy nevertheless has to be strong enough to bring about the changes in technology and energy demand necessary to stabilise at the chosen level.

Compared with the assumptions lying behind the estimates of the social cost of carbon reported in the DEFRA study, there are a number of aspects of this Review’s framework of analysis that tend to push up the implied social cost of carbon. These include:

- The adoption of a full ‘expected utility’ approach to valuation of impacts, allowing risk aversion to give more weight to the possibility of bad outcomes
- Greater weight given to ‘non-market’ outcomes, especially life chances in poor countries[18]
- The use of a low pure rate of time preference, reflecting the view that this rate should be based largely on the probability that future generations exist, rather than their having some more lowly ethical status[19]
- Equity weighting
- The weight given to recent work on uncertainty about climate sensitivity
- The weight given to recent work on amplifying-feedback risks within the climate system to global temperatures and the risks of extreme events

Policy should ensure that abatement efforts intensify over time. Emissions reductions should be driven to the point where their marginal costs keep pace with the rising social cost of carbon.

Firms and individuals are likely to undertake abatement activities up to the point where the marginal costs of reducing carbon emissions are equal to the carbon price, given by the social cost of carbon associated with the desired trajectory. Anticipated improvements in the overall efficiency of emissions reductions should be reflected in quantity adjustments – lower emissions – not a fall in the price of carbon. The rising SCC is driven by the rising atmospheric concentration of greenhouse gases and the marginal abatement costs are brought into equality with the SCC by firms’ and households’ reactions to the carbon price. This is illustrated in Box 13.2.

Marginal abatement costs are a measure of effort. If in any region or sector they fall below the estimated social cost of carbon, not enough is being done – unless emissions have ceased. Over time, it may become much easier to reduce emissions in some sectors. Some models suggest an eventual fall in marginal abatement costs in the energy sector, for example, as a result of technological progress. If that does happen, the sector can become completely decarbonised. But elsewhere, where complete decarbonisation will not have taken place – for example, transport – efforts should increase over time and the marginal abatement cost should continue to rise. But policy-makers should foster the development of technology that can drive down the *average* costs of abatement over time.

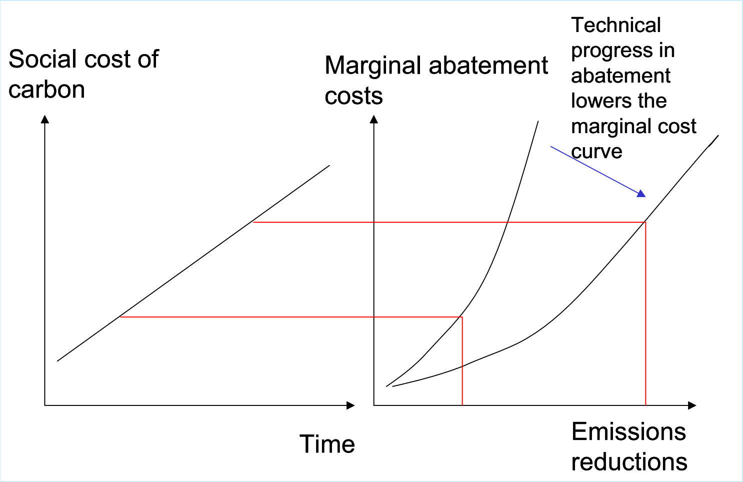
---

[17] Watkiss et al. (2005)

[18] While we have counselled against excessively formal monetary approaches to the value of life, losses of life from climate change nevertheless should weigh heavily in any assessment of damages from climate change.

[19] Note that this is not the same as a low discount rate. The higher the growth rate, the higher the discount rate (see Chapter 2 and its appendix).

Box 13.2 The relationship between the social cost of carbon and emissions reductions



Up to the long-run stabilisation goal, the social cost of carbon will rise over time because marginal damage costs do so. This is because atmospheric concentrations are expected to rise and damage costs are expected to be convex in temperature (i.e. there is increasing marginal damage); these effects are assumed to outweigh the declining marginal impact of the stock of gases on global temperature at higher temperatures.

The price of carbon should reflect the social cost of carbon. In any given year, abatement will then occur up to this price, as set out in the right-hand panel of the diagram above. Over time, technical progress will reduce the total cost of any particular level of abatement, so that at any given price there will be more emission reductions.

The diagram reflects a world of certainty. In practice, neither climate-change damages nor abatement costs can be known with certainty in advance. If the abatement-cost curve illustrated in the right-hand panel were to fall persistently faster than expected, that would warrant revising the stabilisation goal downwards, so that the path for the social cost of carbon in the left-hand panel would shift downwards.

Delay in taking action on climate change will increase total costs and raise the whole trajectory for the social cost of carbon. The difference between the social cost of carbon on the ‘business as usual’ trajectory and on stabilisation trajectories reflects the fact that a tonne of greenhouse gas emitted is more harmful and more costly, the higher concentration levels are allowed to go. Delay allows excessive accumulation of greenhouse gases, giving decision-makers a worse starting position for implementing policies.

Box 13.3 The social cost of carbon and stabilisation

Pearce (2005)[20] reports a range of estimates of the social cost of carbon on 'optimal' paths towards stabilisation goals. The approach of Nordhaus and Boyer (2000) is perhaps closest in spirit to ours. They derive an estimate of only \$2.48/tCO_2 (converted to CO_2, year 2000 prices) for 2001-2010. But they have a low 'business as usual' scenario, do not apply equity weighting and use a discount rate of 3%, which is a little higher than our approach would usually imply.

Further work on what social cost of carbon corresponds to potential stabilisation levels is needed. Current studies disagree about the values and use different methods to tie down the trajectory through time. The US CCSP review reports values of \$20/tCO_2, \$2/tCO_2 and \$5/tCO_2 in 2020 for a stabilisation level of 550ppm CO_2e in the three studies covered. Edenhofer et al. report estimates of the social cost of carbon ranging from 0 to around \$12/tCO_2 in 2010 for the same stabilisation level (year 2000 prices). Most of the models reviewed envisage the social cost of carbon rising over time, with the level and rate of growth sufficient to pull through the required technologies and reductions in demand for carbon-intensive goods and services.

Preliminary calculations with the model used in Chapter 6 suggest that the current social cost of carbon with business as usual might be around \$85/tCO_2 (year 2000 prices), taking the baseline climate sensitivity assumption used there, if some account is taken of non-market impacts and the risk of catastrophes, subject to all the important caveats discussed in Chapter 6. But along a trajectory towards 550ppm CO_2e, the social cost of carbon would be around \$30/tCO_2 and along a trajectory to 450ppm CO_2e around \$25/tCO_2e. These numbers indicate roughly where the range for the policy-induced price of emissions should be if the ethical judgements and assumptions about impacts and uncertainty underlying the exercise in Chapter 6 are accepted.

It would only make sense to have chosen a 550ppm CO_2e target in the first place if a carbon-price path starting at \$30/tCO_2 had been judged likely to be sufficient (together with other policies) to pull through over time the deployment of the technological innovations required. Similarly, it would only make sense to have chosen a 450ppm CO_2e target if a price path starting at \$25/tCO_2e had been judged sufficient to bring through the technology needed.

The social cost of carbon[21] can be used to calculate an estimate of the benefits of climate-change policy. The gross benefits of policy for a particular year can be approximated by

$$(SCC_H \times E_H) - (SCC_S \times E_S)$$

where SCC denotes the social cost of carbon, E the annual level of emissions, the subscript H the high 'business as usual' trajectory and the subscript S the stabilisation trajectory[22]. This is the net present value of the flow of damages from emissions on the high path less the net present value of the flow of damages on the lower path. With sensible policies ensuring that marginal abatement costs equal the social cost of carbon along the stabilisation trajectory, and assuming for simplicity's sake that marginal abatement cost is equal to average abatement cost[23], the annual costs of abatement can be approximated by

$$SCC_S \times (E_H - E_S)$$

Hence benefits less costs are equal to

$$(SCC_H \times E_H) - (SCC_S \times E_S) - (SCC_S \times (E_H - E_S)) = (SCC_H - SCC_S) \times E_H$$

Thus an approximation of the net present value of the benefits of climate-change policy in any given year can be obtained by multiplying 'business as usual' emissions by the difference between the social costs of carbon on the two trajectories. Calculations for this Review

---

[20] Pearce (2005)

[21] The social cost of carbon has to be expressed in terms of some numeraire. Typically the change in consumption that brings about the same impact on the present value of expected utility is used. But that depends on the level of consumption one starts with, so the numeraire differs when comparing significantly different paths. Hence these calculations are strictly valid only if consumption along one or other of the two paths (or some weighted average) is used as numeraire for the calculation of both SCCs.

[22] Because the social cost of carbon is a function of the stock of greenhouse gases, not the flow of emissions, it is insensitive to the variation of emissions in a single year.

[23] This is equivalent to assuming constant returns to scale in abatement over time. In fact, we would expect the average abatement cost to be lower than the marginal abatement cost, with dynamic returns to scale reducing them over time, so this simplification gives an underestimate of the benefits of climate-change policy.

suggest that the social cost of carbon on a reasonable stabilisation trajectory may be around one-third the level on the 'business as usual' trajectory, implying that the net present value of applying an appropriate climate-change policy this year might be of the order of $2.3 – 2.5 trillion. This is not an estimate of costs and benefits falling in this year, but of the costs and benefits through time that could flow from decisions this year; many of these costs and benefits will be in the medium- and long-term future. It is very important, however, to stress that such estimates reflect a large number of underlying assumptions, many of which are very tentative or specific to the ethical perspectives adopted.

13.10 The role of adaptation

Adaptation as well as mitigation can reduce the negative impacts of future climate change.

Adaptation reduces the damage costs of climate change that does occur (and allows beneficial opportunities to be taken), but does nothing direct to prevent climate change and is in itself part of the cost of climate change. Mitigation prevents climate change and the damage costs that follow. Stabilisation at lower levels would entail less spending on adaptation, because the change in climate would be smaller. That needs to be taken into account when considering how total costs change with changes in the ultimate stabilisation level. Similarly, for lower stabilisation levels, a given increase in spending on adaptation is likely to have a bigger effect in lowering the costs of climate change than the same increase at higher concentration levels (because of declining returns to scale for adaptation activities)[24].

There are important differences between adaptation and mitigation that differentiate their roles in policy.

First, while those paying the costs will often capture the benefits of adaptation at the local level, the benefits of mitigation are global and are experienced over the long run. Second, because of inertia in the climate system, past emissions of greenhouse gases will drive increases in global mean temperature for another several decades. Thus mitigation will have a negligible effect in reducing the cost of climate change over the next 30-50 years: adaptation is the only means to do so.

Adaptation can efficiently reduce the costs of climate change while atmospheric concentrations of greenhouse gases are being stabilised.

A stabilisation goal facilitates adaptation by allowing a better understanding to develop of what ultimately societies will have to adapt to. Work using Integrated Assessment Models (IAMs, discussed in Chapter 6) has identified significant opportunities to reduce damage costs through adaptation. There are many reasons other than assumptions about adaptation why the predictions of one model differ from another[25]. It is nevertheless intuitive that those models with the most comprehensive adaptation processes estimate the lowest damage costs and highest adaptation benefits[26]. Studies at a more local level of the costs and benefits of adaptation usually point to net benefits, so some is likely to take place, although policy measures are often required to overcome barriers (see Part V). Adaptation will have a particular role to play in low-income regions, where vulnerability to climate change is higher. In such regions, there are strong complementarities between development policies in general and adaptation actions in particular.

There are further examples of complementarities:

- Mitigation reduces the likelihood of dangerous climate change, which makes adaptation either infeasible or very costly;
- Mitigation reduces uncertainty about the range of possible climate outcomes requiring adaptation decisions. Uncertainty is a clear impediment to successful adaptation.

---

[24] Part V considers adaptation in detail. The key point here is that adaptation is likely to become more expensive and less effective as global temperatures rise further.

[25] Hanemann (2000).

[26] In particular, Mendelsohn et al. (2000).

In the longer run, both adaptation and mitigation will be required to reduce climate-change damage in cost-effective and sustainable ways.

They should not be regarded as alternatives. Part II outlined why the damage costs of climate change are likely to increase more rapidly as global mean temperatures increase. As Part V explains in more detail, attempts at adaptation would not be an adequate response to the pace and magnitude of climate change at high global mean temperatures compared with pre-industrial levels. Ecosystems, for instance, cannot physically keep pace with the shifts in climatic conditions implied. The adaptation that remains viable is likely to be very costly. Without mitigation, little can reduce the underlying acceleration in climate-change impacts as temperatures rise. This is why promoting development in developing economies, while vital in its own right and helpful in building the capacity to adapt, is not an adequate response by itself. Mitigation is the key to reducing the probability of dangerous climate change, given the scale of the challenge. A strategy of mitigation plus adaptation is superior to ‘business as usual’ plus adaptation, and requires less spending on adaptation.

13.11 Conclusions

This chapter has considered in broad terms what climate-change policy should aim to achieve, given the evidence about the risks of serious damages from climate change and the costs of cutting greenhouse-gas emissions. The first priority is to strengthen global action to slow and stop human-induced climate change and to start undertaking the necessary adaptation to the change that will happen before stability is established. The benefits of doing more clearly outweigh the costs. Delay would entail more climate change and eventually higher costs of tackling the problem. The nature of the uncertainties in the science and economics warrants more action not less.

Once the case for stronger global action is accepted, the question arises, how much? We have argued the merits of organising the discussion of this problem around the idea of a goal for the ultimate concentration of greenhouse gases in the atmosphere. Choosing a specific level or range for such a goal should help to make policies around the world more consistent, coherent and cost-effective. In particular, choosing a goal helps to define and anchor a path for the carbon price, a key tool for implementing climate-change policy. The next part of this Review examines in more detail the types of policy instruments that need to be used to reduce greenhouse-gas emissions cost-effectively and on the scale required.

References

Arnell, N.W., M.J.L. Livermore, S. Kovats et al. (2004): ‘Climate and socio-economic scenarios for global-scale climate change impacts assessments: characterising the SRES storylines’, Global Environmental Change **14**:3-20

Clarkson, R., and K. Deyes (2002): ‘Estimating the social cost of carbon emissions’, GES Working Paper 140, London: HM Treasury.

Downing, T.E., D. Anthoff, R. Butterfield et al. (2005): 'Social cost of carbon: a closer look at uncertainty'. London: Department of Environment, Food, and Rural Affairs (DEFRA), available from http://www.DEFRA.gov.uk/ENVIRONMENT/climatechange/carboncost/index.htm

Edenhofer, O., K. Lessmann, C. Kemfert, et al. (2006): ‘Induced technological change: exploring its implications for the economics of atmospheric stabilization: synthesis report from the innovation modeling comparison project’, The Energy Journal, special issue, April: 57-108

Hanemann, W.M. (2000) 'Adaptation and its measurement' Climatic Change 45 (3-4): 571-581

Hope, C. (2003): ’The marginal impacts of CO2, CH4 and SF6 emissions,’ Judge Institute of Management Research Paper No.2003/10, Cambridge, UK, University of Cambridge, Judge Institute of Management.

Ingham, A, and Ulph, A (2005): ‘Uncertainty and climate-change policy’ in Helm, D (2005): Climate-change policy, Oxford: Oxford University Press.

IAG (2005): 'Evidence to the Stern Review on the economics of climate change', Melbourne: Insurance Australia Group, available from http://www.sternreview.org.uk

Kolstad, C. (1996): ‘Fundamental irreversibilities in stock externalities’, Journal of Public Economics, **60**: 221-233

Mendelsohn, R.O., W.N. Morrison, M.E. Schlesinger and N.G. Andronova (1998): ’Country-specific market impacts of climate change‘, Climatic Change 45(3-4): 553-569. (change the citation to Mendelsohn et al. (1998).

Nordhaus, W., and J.G. Boyer (1999): 'Roll the DICE Again: Economic Models of Global Warming', Cambridge, MA: MIT Press.

Pindyck, R. (2000): ‘Irreversibilities and the timing of environmental policy’, Resource and Energy Economics, **22**: 233-259

Manne**,** A. and R. Richels, 1995: The greenhouse debate: economic efficiency, burden sharing and hedging strategies. *The Energy Journal*, **16(4),** 1-37.

Pearce, D. (2005): ‘The social cost of carbon’ in Helm, D (2005): Climate-change policy, Oxford: Oxford University Press.

Schlenker W. and M.J. Roberts (2006): ‘Nonlinear effects of weather on corn yields’, Review of Agricultural Economics **28**: in press.

Tol, R.S.J. (1997), 'On the optimal control of carbon dioxide emissions: an application of FUND' *Environmental Modelling and Assessment*, **2**, 151-163.

Tol, R.S.J. (2005): ‘The marginal damage costs of carbon dioxide emissions: an assessment of the uncertainties’, Energy Policy, **33**: 2064-2074

US CCSP Synthesis and Assessment Product 2.1, Part A: ‘Scenarios of greenhouse gas emissions and atmospheric concentrations’, Draft for public comment, June 26, 2006.

Watkiss, P. et al. (2005): ’The social cost of carbon’, London: DEFRA, December.