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 use 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 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].

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[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.

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[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.

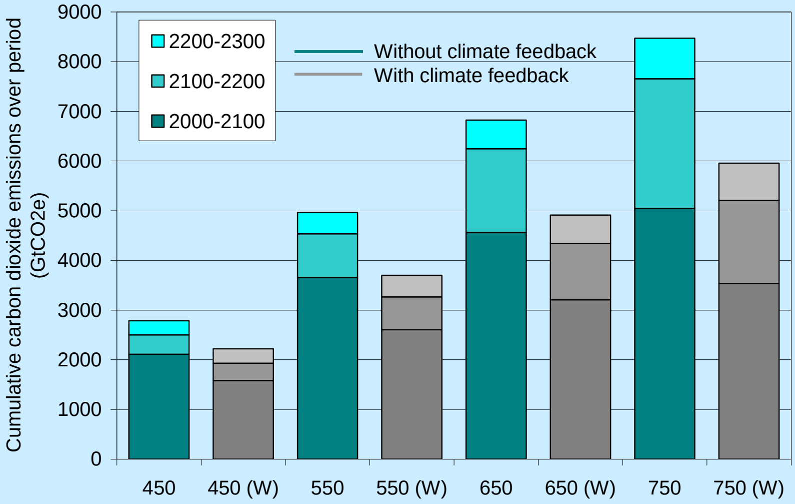
[3] Based on Jones *et al.* 2006, assuming no climate-carbon feedback.

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

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[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

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[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

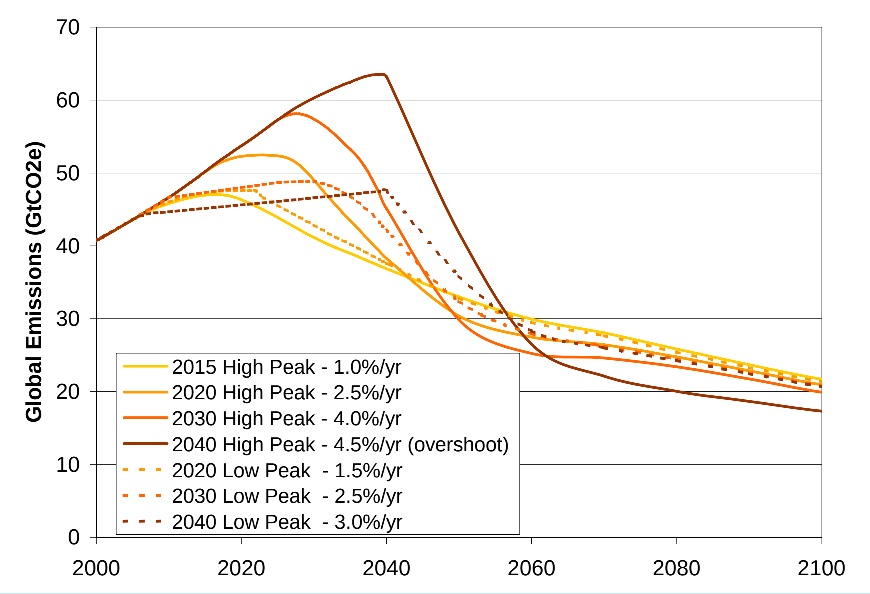
As discussed above, stabilisation at any level ultimately requires a cut in emissions down to less than 20% of current levels. The question then becomes one of how quickly stabilisation can be achieved. If action is slow and emissions stay high for a long time, the ultimate level of stabilisation will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

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[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_2e)	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 $GtCO_2e$/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_2e, 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_2e. A higher stabilisation level would require weaker cuts. For example, to stabilise at 650 ppm CO_2e, 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.

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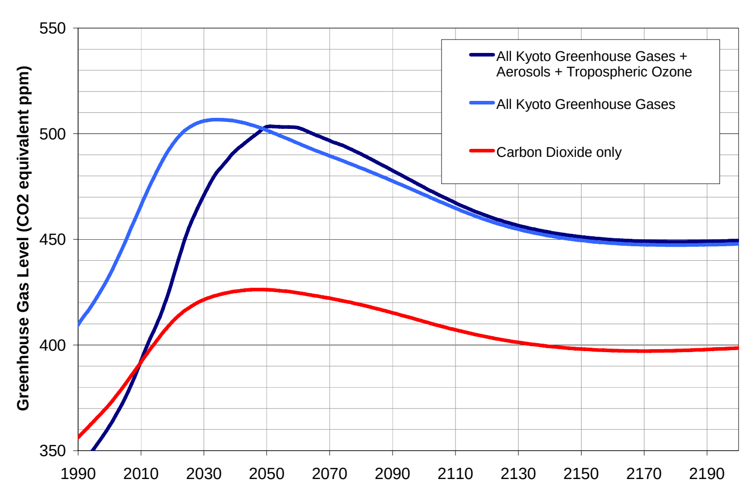
[11] An atmospheric greenhouse gas level of 450 ppm is less than 10 years away, given that concentrations are rising at 2.5 ppm per year (chapter 3). However, in the scenarios outlined in Table 8.1, aerosol cooling temporarily offsets some of the increase in greenhouse gases, giving more time to stabilise.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

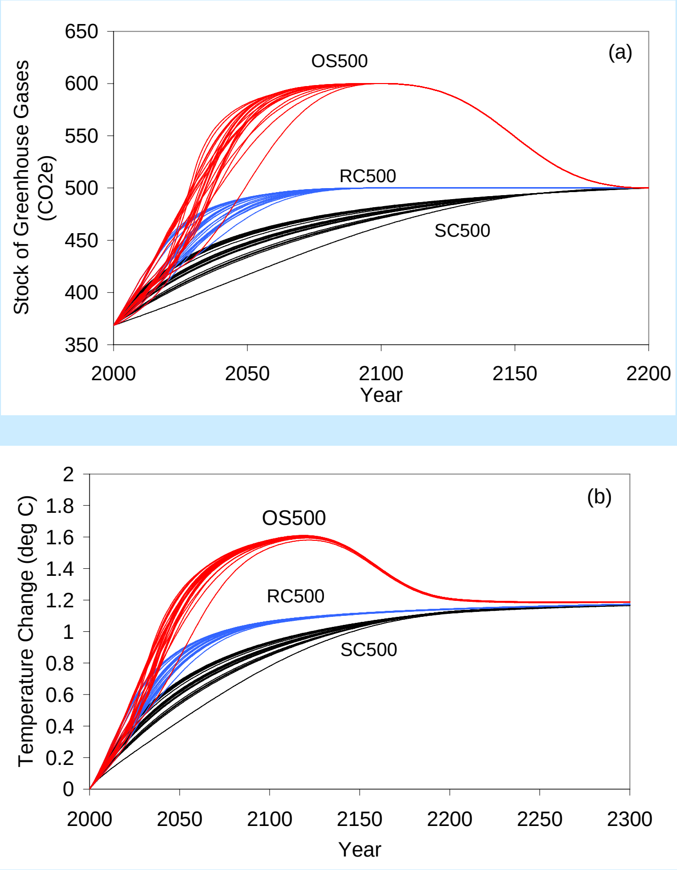
Delaying action risks getting 'locked into' long-lived high carbon technologies. It is crucial to invest early in low carbon technologies. Technology policies are discussed in chapter 15.

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.

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[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 $GtCO_2e$ 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 $GtCO_2e$ in 2050 to stabilise at 450 – 550 ppm CO_2e. For comparison, total global emissions are currently around 45 $GtCO_2e$ 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.

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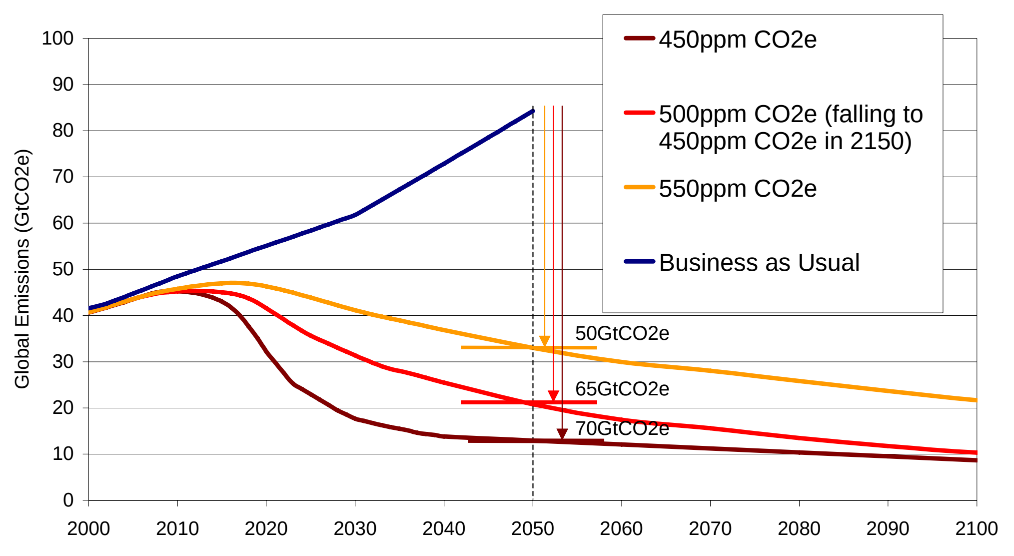
[14] Business as usual (BAU) used in this chapter is described in chapter 7.

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.

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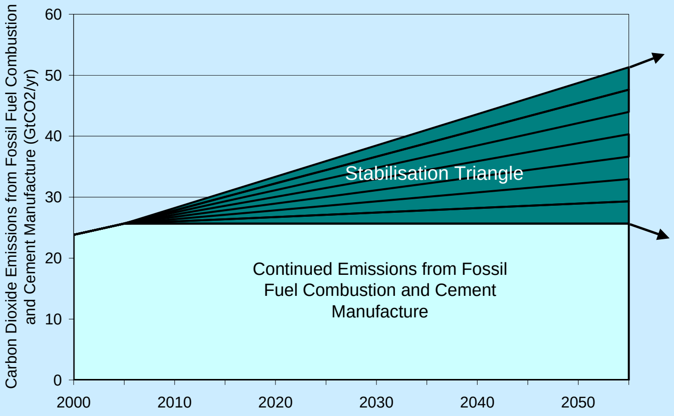
[15] Annex I includes OECD, Russian Federation and Eastern European countries. This is discussed further in Part IV.

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.

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