Reducing the Pressure: Potential for mitigation

This chapter has been co-authored with Dr Lenny Bernstein

This chapter looks at the potential to reduce greenhouse gas emissions over the next few decades (up to about 2030) and the policies required to achieve this, as well as the costs involved. Most of the potential that can be quantified comes from technological changes or replacement of a high-emissions technology with a low-emissions alternative. The technologies we discuss in this chapter are already available or expected to be commercialised in the next few decades. However, this does not mean that all available technologies to reduce emissions will be used. We, therefore, also look at the range of policies available to governments to promote the implementation of mitigation options and to remove barriers to their uptake where this is cost-effective.

This chapter is mainly concerned with what mitigation options are available and how they can be implemented. Chapter 7 takes a longer-term look to see at what level greenhouse gas concentrations would eventually stabilise if we pursue those mitigation options and what long-term level of climate change this would imply, what long-term technological shifts various mitigation paths would require, and what costs to the global economy and prices on carbon this would entail.

Chapter 6 draws its material (and some of its wording) almost entirely from the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC), specifically the Working Group III Report (WGIII), which contains an extremely detailed discussion of mitigation options and costs. It is worth emphasising that the literature on mitigation is growing extremely rapidly, particularly on carbon markets, emissions trading systems, and some new technologies, and their effectiveness and costs. However, it would go beyond the scope of this book (and my expertise) to try to provide a comprehensive update in all these areas. Additional references from the more recent literature are provided mainly on biofuels, where developments over the past two years have sharply highlighted the potential risks and opportunities in this area.

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6.1 Climatic benefits of reducing greenhouse gas emissions

Chapter 5 considered the options we have to reduce the adverse impacts of climate change by adapting to those changes and increasing the resilience of ecosystems and human society. The complementary response is to reduce the rate and magnitude of future human-induced climate change, and thus limit the pressure that its impacts create on ecosystems and human society in the first place. 36

As discussed in chapters 2 and 3, emissions of long-lived greenhouse gases from human activities, particularly carbon dioxide (CO₂), would have to fall far below current levels to halt the growth of greenhouse gas concentrations (see Box 2.1). But even when concentrations of all greenhouse gases are eventually stabilised, temperature and sea levels will continue to creep up further until they eventually stabilise over the course of many more centuries.

Figure 6.1 shows schematically this general relationship between greenhouse gas emissions, concentrations, and temperature change until 2100, for scenarios with and without mitigation measures. The scenarios that assume no additional measures to reduce greenhouse gas emissions are based on the Special Report on Emissions Scenarios (SRES; IPCC, 2000; see section 3.2). The mitigation scenarios (shown as two idealised cases) would reduce greenhouse gas emissions below these baseline levels and stabilise concentrations by or shortly after the end of the 21st century, and lead to a reduced rate and absolute amount of warming over the 21st century and beyond.

Figure 6.1 shows this relationship only in broad illustrative terms because no detailed model simulations of the climate response to specific mitigation scenarios were available in the recent IPCC assessment report. Several more recent studies have quantified the likely temperature increases under stringent mitigation scenarios until the end of the 21st century, using simple climate models to emulate the outcomes of more complex models. These studies indicate that the most stringent mitigation scenarios, where CO₂ emissions drop to zero or even become negative by the end of the 21st century, would limit the temperature increase by 2100 and beyond to about 1.5°C relative to 1980–1999 (as a best estimate), or about 2°C relative to pre-industrial conditions (see, eg, Meinshausen et al, 2006; Meinshausen et al, 2008; van Vuuren et al, 2008; Meinshausen et al, 2009). By comparison, the lowest SRES scenario gives a best-estimate warming of about 2.3°C by the 2090s relative to pre-industrial conditions, and implies further warming beyond 2100. The top end of the SRES scenarios leads to a best-estimate warming of about 4.5°C relative to pre-industrial conditions, with several degrees of more warming likely beyond 2100 (see sections 3.3 and 3.5).

36 Some people refer to adaptation as ‘the ambulance at the bottom of the cliff’ and regard mitigation as the safety barrier at the top of the cliff. I do not like this metaphor because it sounds as if we are either on top of the cliff or at its bottom. However, we find ourselves mostly in between: we are already falling, but we have yet to hit the ground. Climate impacts will continuously affect people, regions, and sectors around the world in various ways as time goes along.
Depending on the assumed baseline (i.e., the emissions one assumes would occur in the absence of any dedicated climate policies), the climatic benefits of implementing mitigation technologies and policies could range from 0.5°C to 3°C by 2100, and much more beyond 2100 since temperatures continue to rise beyond 2100.\[37\]

In general terms, the lower the long-term stabilisation level, the more quickly emissions would have to reach their peak and fall to low levels. However, temperatures and sea level would continue to increase long after emissions have started to decline. One important consequence of this inertia in the climate system is that, for the next two decades, even stringent mitigation is unlikely to make a major difference on global temperatures and climate change. The main benefits of mitigation (in terms of reducing climate change and the associated impacts and risks) will accrue only gradually, first by reducing the rate of climate change, and only in the longer term (in the second half of the 21st century and beyond) by reducing the absolute amount of change.

This delayed climatic benefit of mitigation does not mean that one can or should wait with emission reductions: if we want mitigation to substantially reduce climate change by the second half of the 21st century, then we need to start now. If we delay mitigation actions until the second half of the 21st century, their climatic benefits would become significant only in the 22nd century, and so on. In other words, mitigation efforts have to be in place a significant time before the climatic benefits of these actions would become apparent. This makes mitigation a tough political challenge, because there is no immediate climatic payback for such efforts. Mitigation can have co-benefits that become much more immediately apparent, such as reduced air pollution and health benefits. We consider co-benefits in chapter 9 when we place adaptation and mitigation in the wider context of sustainable development.

This chapter focuses on the technological and policy options and costs in the 'near-term' (i.e., up to about 2030) to reduce greenhouse gas emissions, relative to projected emissions increases under non-mitigation scenarios. However, even the most stringent efforts cannot reduce global emissions to zero by 2030, which means the concentrations of the longest lived greenhouse gases will still continue to rise. Chapter 7, therefore, discusses the long-term technological changes needed to reduce emissions further beyond 2030 so that greenhouse gas concentrations stabilise at least by 2100 or beyond, and the global economic costs and long-term climatic consequences that different levels of effort would entail. Chapter 8 then discusses the crucial question of how we might decide on how much mitigation is necessary, and how urgent it is in the light of current information about climate change impacts and adaptation options.

\[37\] Note that even though the lowest SRES scenario is not a mitigation scenario, it nonetheless assumes a significant improvement in energy efficiency and energy generation technology, as well as a massive shift towards renewable energy sources and reduced emissions of non-CO\(_2\) gases compared to the present. In this scenario, these shifts are assumed to happen for non-climatic reasons such as the global economy moving away from commodities and towards services, and other environmental concerns about fossil fuel extraction, health effects, and sustainability of farming and food production (IPCC, 2000). As we see in chapter 9, some policies that reduce greenhouse gas emissions have important other health, energy security, and environmental co-benefits, and vice versa. The distinction between the lower end of the non-mitigation SRES scenarios and the upper end of the mitigation scenarios, therefore, is somewhat blurry.
Figure 6.1: Emissions, concentrations, and temperatures for mitigation and non-mitigation scenarios

Note: Schematic representation of emissions (left panel), concentrations (middle panel), and resulting changes in global average temperature (right panel) from 1990 to 2100 for two idealised stabilisation scenarios (blue and red lines) and the range of non-mitigation scenarios from the Special Report on Emissions Scenarios (IPCC, 2000; grey shaded areas).

Source: Based on IPCC (2000) and WGIII 3.2 and 3.3; for additional references from the recent literature, see the text.
6.2 The challenge of rising emissions

6.2.1 Emissions trends

The goal of reducing the pressures from climate change by reducing greenhouse gas emissions starts with an uphill battle. Emissions of greenhouse gases from human activities have been rising strongly since pre-industrial times, with an increase of about 70% alone between 1970 and 2004 (from 28.7 gigatonnes CO$_2$ equivalent (GtCO$_2$-eq) to 49 GtCO$_2$-eq). The rate of growth of CO$_2$-equivalent emissions accelerated over the past decade; during 1995–2004, emissions increased on average by about 0.92 GtCO$_2$-eq every year, while during 1970–1994 emissions increased on average by about 0.43 GtCO$_2$-eq every year. (WGIII 1.3)

Figure 6.2 shows how emissions of the main greenhouse gases generated by human activities grew from 1970 to 2004. CO$_2$ is the most important greenhouse gas from human activities; it grew by 80% from 1970 to 2004 and represented 77% of the total CO$_2$-equivalent emissions in 2004. Methane (CH$_4$), nitrous oxide (N$_2$O), and fluorinated gases together make up just under one-quarter of these total emissions. (WGIII 1.3)

All sectors contribute to the emissions of greenhouse gases, including direct energy supply in the form of electricity and heat, transport, the construction, heating, and cooling of buildings, industrial processes, agriculture, forestry and deforestation, and waste management. The sectors and specific activities that contribute to greenhouse gas emissions are indicated schematically in Figure 6.3 along with the share of different sectors and gases to the total greenhouse gas emissions by human activities.

By far the most CO$_2$ emissions come from the burning of fossil fuels, which are converted into other forms of energy in the energy supply, transport, industry, and buildings sectors. Another significant but smaller fraction of CO$_2$ emissions comes from deforestation and decay of biomass. The largest relative growth in emissions since 1970 occurred in energy supply (145%) and transport (120%), followed by industry (65%), and forestry including deforestation (40%). Emissions from agriculture and residential/commercial buildings grew at smaller rates of 26% and 27% respectively. (WGIII 1.3)

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38 These figures do not include emissions of ozone-depleting substances that are also greenhouse gases, such as chlorofluorocarbons, or greenhouse gases that are not directly emitted but nonetheless influenced by human activities such as ground-level ozone resulting from urban air pollution. Gases that contribute to ozone depletion are controlled under the Montreal Protocol, which is part of the Vienna Convention for the Protection of the Ozone Layer. Their production is being phased out globally, so their concentrations are expected to gradually decline in the atmosphere. For more details on these gases and the options to control their emissions, see the Special Report on Safeguarding the Ozone Layer and the Global Climate System (IPCC and TEAP, 2005).
Figure 6.2: Emissions trends in greenhouse gases, 1970–2004

Global anthropogenic greenhouse gas emissions 1970–2004

Notes: CH$_4$ = methane; CO$_2$ = carbon dioxide; CO$_2$-eq = carbon dioxide equivalents; HFCs = hydrofluorocarbons; N$_2$O = nitrous oxide; PFCs = perfluorocarbons; SF$_6$ = sulphur hexafluoride. The figure shows trends since 1970 in emissions of the greenhouse gases controlled under the Kyoto Protocol by broad sectors. Some ozone-depleting gases are also greenhouse gases; these gases (such as chlorofluorocarbons) are not included in this figure because they are already controlled and being reduced through the Montreal Protocol. Source: Based on WGIII Figure 1.1 and data in WGIII 1.3.
Figure 6.3: Contributions of different sectors, processes, and gases to total greenhouse gas emissions

Note: The schematic diagram illustrates the relative contributions of different sectors and gases to global CO₂-equivalent greenhouse gas emissions in 2004. The left-hand pie chart shows the relative contributions of different sectors, while the right-hand pie chart shows the relative contributions of different greenhouse gases to total emissions (measured in CO₂-equivalents; data from WGIII 1.3). The central diagram shows how various sectors and sector-specific processes contribute to the emission of different greenhouse gases (flows of greenhouse gases from sectors and activities are derived from Figure 1.3 in Baumert et al, 2005, used with the kind permission of the World Resources Institute). The left-hand pie chart allocates emissions to the sector where the emissions occur, that is, emissions arising from the supply of energy that is consumed for the heating and cooling of buildings is attributed to the energy supply sector, not to the building sector. If we instead allocate emissions to the sectors where energy is used, buildings and industry would hold a much larger share of total emissions.
6.2.2 Past and future drivers for rising global emissions

What has driven this enormous increase in emissions, particularly the emissions of CO\(_2\) that are related to energy in the form of energy supply, transport, industrial uses, and buildings? We can dissect the drivers behind this growth through a simple equation:

\[
\text{CO}_2 = \text{population} \times \text{GDP per capita} \times \text{energy per unit of GDP} \times \text{CO}_2 \text{ emissions per unit of energy}
\]

This equation identifies the drivers of energy-related CO\(_2\) emissions as population, wealth, the energy intensity of the economy (ie, how much energy we use to power our economy), and the carbon intensity of energy supply (ie, how much CO\(_2\) we emit on average for each unit of energy that we produce).

Globally, both population and global gross domestic product (GDP) per capita rose from 1970 to 2000 and contributed in almost equal measure to the growth in energy-related CO\(_2\) emissions. Global consumption of energy more than doubled over this period. Global GDP increased more rapidly after 2000 and was the main driver of CO\(_2\) emissions growth during the early years of the 21st century until the economic downturn that began in 2008. The energy intensity of the global economy and to a lesser extent the carbon intensity of energy supply steadily decreased since 1970, but these improvements were not sufficient to offset the two growth factors. The trend of a declining carbon intensity of energy supply reversed after 2000, reflecting the greater use of coal, which emits larger amounts of CO\(_2\) per unit of energy than other fossil fuels. (WGIII 1.3)

Most of the growth in energy consumption since 1970 occurred in the rapidly developing economies of east and south-east Asia, but energy consumption increased in all regions of the world. The smallest growth occurred in countries belonging to the former Soviet Union that experienced a massive economic slow-down in the early 1990s and are now transitioning towards market economies operating at higher efficiency (so called ‘countries with economies in transition’). (WGIII 1.3, 4.1)

Emissions of greenhouse gases are very unevenly distributed around the world. Figure 6.4 shows total emissions as well as average emissions per capita and per unit of GDP for different regions for 2004. The highest emissions per capita typically come from developed countries and countries with economies in transition, which collectively hold only 20% of the world’s population but produce 46% of greenhouse gas emissions. This picture is almost reversed when we look at the carbon intensity of economies: developed countries emit on average significantly lower amounts of greenhouse gases for each dollar they produce than developing countries and countries with economies in transition. (WGIII 1.3; SYR 2.1)

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39 The equation is also known as the ‘Kaya-identity’. It’s not another best-selling CIA thriller but named after the person who first proposed it, Yoichi Kaya, following the Conference on Global Environment, Energy, and Economic Development in Tokyo, Japan, in 1993.
Figure 6.4: Absolute and per capita greenhouse gas emissions and gross domestic product for different world regions

Note: The figure shows the contribution of various regions to global emissions of greenhouse gases (blue bars), and the emissions per capita and per unit of gross domestic product (GDP) within each region, for 2004 (blue, orange and yellow bars, respectively). Developing countries typically have much lower emissions per capita but higher emissions per unit of GDP than developed countries. Absolute emissions from some developing country regions, particularly south and east Asia, are comparable to emissions from Europe and North America.

Source: Based on data from SYR 2.1, Figure 2.2.
Emissions are projected to keep increasing for at least the next few decades unless additional policies to reduce greenhouse gas emissions are implemented. As we saw in chapter 3, the SRES scenarios project emissions to increase further by 25–90% from 2000 to 2030. The main driver for this continued emissions growth is projected increases in wealth, which is projected to contribute more than twice as much to CO$_2$ emission growth as further increases in population (WGIII Figure 1.6). The energy intensity of the economy is expected to continue to improve (ie, less and less energy being needed to deliver the same general level of products and services), but this is not sufficient to offset the overall growth in emissions. The average carbon intensity of energy supply is not expected to improve further in the absence of dedicated mitigation measures over the next few decades because fossil fuels, in particular coal, will remain a comparatively cheap source of power compared with renewable or other low-carbon sources of energy. As a consequence, fossil fuels are expected to retain their dominant position in global energy supply, leading to a rise in energy-related CO$_2$ emissions of 40–110% between 2000 and 2030. (WGIII 1.3, Figure 1.6) The rising cost of oil will unfortunately do little to influence these emissions trends and could in fact fuel further emissions increases (see Box 6.1).

Under all SRES scenarios, emissions until 2030 are expected to grow most strongly in developing countries in Asia, followed by Africa and Latin America, which reflects the projected continued economic and population growth in these regions. Nonetheless, on a per capita basis, emissions and incomes in these regions are projected to remain on average well below those of developed countries. Emissions from developed countries and countries with economies in transition are projected to grow at a slower pace or even fall in some scenarios. (WGIII 1.3, 4.2; SYR 2.2)

The challenge presented by such rising emissions is formidable. If we want to stabilise greenhouse gas concentrations at the lower end of the ranges assessed by the IPCC, global greenhouse gas emissions would have to fall below their year 2000 levels by 2030 and continue to decline strongly thereafter (see also chapter 7). Given the projected growth in emissions without mitigation measures, is this a feasible goal or an unrealistic hope? The next sections address this question by looking at mitigation options in various sectors and combining the potential across sectors and across different regions of the world.

**Box 6.1: Will rising oil prices automatically lead to lower greenhouse gas emissions?**

One might assume that the rising cost of fossil fuels will automatically lead to lower greenhouse gas emissions. Unfortunately, this is not necessarily true. While the availability of cheap oil and gas will very likely decline over coming decades, there are ample supplies of oil in tar sands and oil shales whose extraction becomes economical if the price of crude oil rises. In addition, coal will remain an abundant and key source of energy for many developed and developing countries. In fact, in the first few years of the new millennium, the rising cost of oil mainly led to an increased use of coal, which resulted in a significant rise in global energy-related carbon dioxide emissions rather than a decline. (WGIII 1.3)
The choice of future energy sources will depend on their costs, the security of supply, priorities for economic development, and local and global environmental impacts. A rise in oil prices, therefore, will not automatically lead to a large-scale shift to renewables. Coal is cheap and abundant, and likely to fuel most new electricity generating capacity to 2030. Oil is used primarily in the transport sector. Unconventional oil from tar sands and oil shale is more expensive and generates higher environmental impacts than conventional oil, but continued use of oil would have the advantage that it avoids significant changes in end-use technology compared with the introduction of hydrogen or electric vehicles. The cheapest sources of renewable energy, wind and large-scale hydro, often face local and environmental opposition, as well as opposition from vested energy industry interests. (WGIII 1.3, 4.1, 4.2, 4.3)

Studies by the International Energy Agency, which explore different scenarios for future prices and availability of fossil-fuel–based and renewable energy sources and take all of the above issues into account, indicate that fossil-fuel–related emissions will continue to increase significantly in the absence of dedicated climate policies regardless of oil prices (see also Bakker et al, 2009). Until at least about 2030, about 80% of the total energy supply will remain based on fossil fuels if no specific climate policies are implemented to promote low- or zero-carbon energy sources.

6.3 Global economic potential for mitigation

6.3.1 Definitions of key terms

Before we discuss the potential to reduce emissions, and how emissions reduction can become reality, we need to be clear about what we mean by the term ‘mitigation potential’; alternative definitions can imply very different meanings. We also need to understand the types of studies that have been used to assess this potential and the implicit assumptions they make.

Four key terms are used extensively in the discussion of mitigation potential. These terms are ‘market mitigation potential’, ‘economic mitigation potential’, and so-called ‘bottom-up’ and ‘top-down’ studies, which are used to estimate these potentials. (WGIII SPM and glossary; SYR 4.3)

Definition of ‘mitigation potential’

The term ‘mitigation potential’ generally describes the amount of emissions that could be reduced or avoided (relative to emissions that would occur otherwise) if we are prepared to pay a given cost and/or reduce barriers to the implementation of mitigation measures.

For example, if companies have to pay $10 for each tonne of CO₂-equivalent that they emit, they have an incentive to reduce their emissions (e.g., by replacing existing technology with more efficient technology) as long as the cost of doing so is equal to or less than $10 for each tonne of CO₂-equivalent that will be reduced or avoided. The amount of emissions reductions that would occur if everybody implemented all possible measures that cost less than $10 per tonne of CO₂-equivalent avoided is called the mitigation potential at $10/tCO₂-eq.
Reducing the Pressure: Potential for mitigation

Not all emissions reductions cost money. Housing insulation is a prime example where the reduced cost of energy used for heating often pays for the added cost of insulation over a few years. In such a case, we talk of the ‘net negative costs’ of mitigation – in other words, benefits. The fact that not all houses are optimally insulated, even though it would save money, shows that it is not just costs that determine whether mitigation potential is realised, but also policies, access to information, and social attitudes.

The emissions reductions that can be achieved for a given price per tonne of CO₂-equivalent depend on whether one takes the perspective of an individual company or of society as a whole, which is captured through the subcategories of ‘market mitigation potential’ and ‘economic mitigation potential’.

**Definition of ‘market mitigation potential’**

The ‘market mitigation potential’ describes the amount of emissions reductions that is cost-effective from the perspective of individual consumers or companies. This takes into account that, in the real world, people have imperfect access to information and there are barriers to using the most cost-effective mitigation options (eg, social attitudes may limit the use of new technologies, or existing policies might provide subsidies to existing products and hence disadvantage new technologies). The market potential also takes into account that the private sector usually wants any investment into new technologies or processes to pay back within a few years or, for very large investments, at most within a couple of decades.

**Definition of ‘economic mitigation potential’**

The ‘economic mitigation potential’ describes the amount of emissions reductions that is cost-effective at a given price of carbon when one takes the perspective of society as a whole and over the long term. The economic mitigation potential assumes everybody has perfect access to information about the most cost-effective emissions reduction options, and that policies are in place to remove barriers to mitigation and ensure cost-effective options are implemented wherever possible. The economic potential also takes a longer-term perspective than the market mitigation potential: it assumes that society as a whole has a lesser need to make short-term returns on its investments than the private sector. For these reasons, the economic mitigation potential is generally greater than the market mitigation potential.

In most studies, and throughout the rest of this chapter, we generally use the economic mitigation potential to describe the potential to reduce emissions and the costs (or benefits) that this would entail for two reasons. First, this book takes a global perspective to describe what mitigation could be achieved at a given cost if (and that is a very big if) proactive and well-designed climate policies were implemented on a global scale and with the benefit of society as a whole in mind.

Second, the economic mitigation potential can be far more objectively determined than the market mitigation potential by looking at what mitigation options are available, how well they work, what they cost, and how such measures interact with other sectors of the economy. This can give us a fairly objective estimate of how much greenhouse gas emissions could be reduced if all relevant measures up to a given cost were fully implemented. By contrast, if we want to estimate the market potential, we need all the above information, but we also need to make assumptions about how much people actually know about mitigation options, how effective existing policies are in practice, how much resistance there is against new technologies or processes, and not least how much some companies might want
to play games with the market or a government (eg, by overstating their costs and thus arguing against climate policies). We would also have to take into account that large international companies have much better access to information than private individuals. It would, therefore, be almost meaningless to describe the market potential in any given sector at a global scale for the next 30 years. Nonetheless, we need to keep in mind that the economic potential refers to an ideal world; the goal of good climate policies is to ensure that as much as possible of the economic potential can and will be realised.

**Definitions of ‘bottom-up’ and ‘top-down’ studies**

The economic mitigation potential can be estimated by two alternative approaches using ‘bottom-up’ or ‘top-down’ studies.

Bottom-up studies look in detail at specific technological, process, and engineering options to reduce emissions in individual sectors and processes. Information about the amount of emissions that could be avoided for a given cost is then aggregated across sectors, and between different world regions, to provide an estimate of the global mitigation potential. In this approach, it is important but difficult to ensure emissions reduction options are not double counted, and to account for interactions between sectors (ie, reducing emissions in one process may make it less cost-effective to reduce emissions somewhere else). Thus, bottom-up studies provide a good ‘nuts and bolts’ perspective, but it can be difficult to put this information together across the economy and across different regions.

Top-down studies use global macroeconomic models. These models are based on historical data regarding consumption, prices, incomes, and the dynamics between different sectors. Using such historical information, these models can tell us how the activity in one sector has changed whenever, for example, energy prices changed, and use this information to predict how the activity of this sector would change if low-carbon technologies increase the cost of energy by a given amount. The advantage of this approach is that it captures the interaction between different sectors and world regions. Its disadvantage is that it does not get into technical details and generally assumes that the current economy is running at its optimum. The very existence of ‘net negative cost’ options to reduce emissions tells us that this is not the case, but most top-down models are by design blind to the existence of such options. Top-down models may also struggle with incorporating adequately the potential for technological improvements in future, although some progress has been made in this area. On the other hand, top-down models assume that there are no costs in switching from one technology to another one. However, this may not be the case in the real world as new technology may be difficult to access, and it may take some time to operate effectively.

This brief description shows that neither top-down nor bottom-up studies are perfect, but neither are hopelessly flawed. We simply need to keep their fundamental assumptions and limitations in mind when interpreting their results to avoid mistaking an assumption that goes into a study for a key finding coming out of the study.

### 6.3.2 Global economic mitigation potential and projected emissions increases

A key conclusion from the AR4 is that the global economic potential for the mitigation of greenhouse gas emissions across all sectors is sufficient to offset the projected growth of emissions over the next few decades, or even to reduce emissions below year 2000 levels by 2030. (WGIII SPM)
The significant economic mitigation potential cannot be delivered for free: reducing emissions places, in many instances, extra costs on society, and the amount of emissions that can be reduced or avoided generally depends on the price we are prepared to pay. In the absence of dedicated mitigation measures, annual greenhouse gas emissions are projected to increase from 40 GtCO$_2$-eq in 2000 to 49.7–76.7 GtCO$_2$-eq by 2030 (i.e., an increase of 9.7–36.7 GtCO$_2$-eq). At costs of up to US$20 for each tonne of CO$_2$-eq avoided, a range of studies suggests that by 2030, 9–18 GtCO$_2$-eq annual emissions could be avoided. At costs up to US$100 the amount of emissions that can be avoided increases to 16–32 GtCO$_2$-eq per year. These estimates are based on technologies and practices that are already available or expected to be commercialised by 2030. (WGIII SPM, 11.3)

Bottom-up studies indicate that 5–7 GtCO$_2$-eq per year could be avoided by 2030 with some economic gain over time. Many of these options exist in the form of energy efficiency improvements in the building sector, where the energy saved in the long term is often greater than the up-front cost of investing in more energy efficient appliances, heating, and insulation. However, the existence of an economic potential to reduce emissions does not mean that these options are also used; they still require policies and information to turn the potential mitigation into reality, for example, to help people to overcome the initial investment hurdle, even if such an investment saves money in the long run. We discuss some of the existing barriers and potential policies to address such barriers later in this chapter.

Figure 6.5 illustrates this potential scale of emission reductions relative to two alternative non-mitigation emissions scenarios. The figure shows that if emissions in the absence of dedicated mitigation measures are assumed to grow only moderately, the economic mitigation potential at US$100/tCO$_2$-eq would be sufficient to reduce emissions well below 2000 levels by 2030. On the other hand, if emissions in the absence of dedicated mitigation measures grow more strongly, the economic mitigation potential at US$100/tCO$_2$-eq would be sufficient to keep emissions constant but not to reduce them below year 2000 levels. Table 6.1 lists the ranges of economic mitigation potential at different costs and compares them with the full range of emissions increases that are projected under the range of SRES (non-mitigation) scenarios (see section 3.2 for details on the SRES scenarios).

The recent IPCC assessment found that bottom-up and top-down studies both come to similar conclusions about the global economic mitigation potential, despite their very different assumptions and approaches (see Table 6.1). This good agreement has increased confidence that the global estimates of economic mitigation potential are real and not based on some faulty or biased assumptions inherent in a specific set of studies. Bottom-up and top-down studies agree less well for the potential in specific sectors. Some of such sectoral disagreements can be explained by different definitions for the various sectors in bottom-up and top-down studies. Some of the differences are likely to be due to the different approaches and assumptions that are used in bottom-up and top-down studies for specific sectors (see also the discussion in section 6.3.1). (WGIII SPM, 11.3)
**Figure 6.5:** Effect of different carbon prices on global greenhouse gas emissions to 2030

Note: The figure shows projected global greenhouse gas (GHG) emissions (in carbon dioxide equivalents (CO₂-eq)) from 2000 to 2030 for two alternative scenarios assuming low (left panel) or medium–high (right panel) emissions growth in the absence of dedicated mitigation measures (thick lines; based on B2 and A1B emissions scenarios from the *Special Report on Emissions Scenarios* (IPCC, 2000)). Both panels also show the emissions that could be reduced by 2030 for carbon prices ranging from $0 to $100 per tonne of CO₂-eq, based on mid-range estimates from bottom-up studies. The emissions reductions for a price of $0/tCO₂ are those that could be achieved at zero or net negative costs if appropriate policies are implemented.

Source: Based on data in WGIII Tables SPM.1 and SPM.2.

**Table 6.1:** Projected emissions increases under the range of *Special Report on Emissions Scenarios* marker scenarios from 2000 to 2030, and economic mitigation potential estimated from top-down and bottom-up studies for a range of carbon prices

<table>
<thead>
<tr>
<th>Carbon price (US$/tCO₂-eq)</th>
<th>Economic mitigation potential in 2030 (GtCO₂-eq)</th>
<th>Emissions growth 2000–2030 for SRES (non-mitigation scenarios) (GtCO₂-eq)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bottom-up studies</td>
<td>Top-down studies</td>
</tr>
<tr>
<td>0</td>
<td>5–7</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>9–17</td>
<td>9–18</td>
</tr>
<tr>
<td>50</td>
<td>13–26</td>
<td>14–23</td>
</tr>
<tr>
<td>100</td>
<td>16–31</td>
<td>17–25</td>
</tr>
</tbody>
</table>

Note: SRES = *Special Report on Emissions Scenarios* (IPCC, 2000); CO₂-eq = carbon dioxide equivalent emissions (for an explanation see Box 3.1); US$tCO₂-eq = price of carbon in United States dollars per tonne of carbon dioxide equivalent emissions; t/Gt = tonnes/gigatonnes; one gigatonne = 10⁹ tonnes.

Source: Based on data in WGIII SPM Tables SPM.1 and SPM.2.

**6.3.3 Global economic mitigation potential across sectors and regions**

To turn the global economic mitigation potential into reality, we need to understand in which sectors and regions those emissions reductions would occur, so appropriate policies can be put in place to achieve them. Figure 6.6 overviews the economic
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mitigation potential for various cost levels in different sectors and world regions. It shows that all major sectors contribute to the overall global potential. For most sectors, the larger proportion of the potential exists in developing countries, which reflects their projected larger emissions growth as well as the higher current energy intensity of their economies and hence opportunities to reduce or avoid those emissions at lower cost. (WGIII SPM, 11.3)

Figure 6.6 also illustrates that in some sectors, such as agriculture, the more money we are prepared to spend, the more emissions we can avoid. In contrast, the mitigation potential for the building sector increases only little with higher costs, because most mitigation options are already available at low (or even no) costs. Note that the mitigation potential for each sector is based on end-use allocations of emissions. This means measures that could reduce energy consumption in, for example, the building sector are counted as having mitigation potential for the building sector, not the energy supply sector. The total figures have been checked for double counting between these sectors. Note that the sectoral estimates do not consider non-technological options such as lifestyle changes, which are considered separately in section 6.4. (WGIII SPM, 11.3)

The following sections take us for each sector through the key technologies that already exist or are expected to be commercialised by 2030, and that together could deliver the total emissions reductions shown in Figure 6.6. No single technology can deliver the economic mitigation potential in any sector. A wide range of technologies and sector-specific support policies are needed to reach the full potential. Relying on only one technology would reduce the total mitigation potential or increase the cost to achieve the same level of emissions reductions. (WGIII 11.3, SPM)

**Figure 6.6:** Economic mitigation potential for different sectors and world regions by 2030

Note: CO₂-eq = carbon dioxide equivalent; EIT = Economies in Transition; OECD = Organisation for Economic Co-operation and Development. The figure shows estimated economic mitigation potential for different sectors and world regions from bottom-up studies, using technologies and practices available now or expected to be available in 2030. The potentials do not include non-technological options such as lifestyle changes and exclude some technological options mainly in transport and high-cost options for buildings. These additional options could increase the total mitigation potential by another 10–15%.

Source: Based on SYR Figure 4.2.
6.4 Sector-specific mitigation options, potentials, policies, and barriers

6.4.1 Energy supply

The supply of energy, mainly in the form of heat and electricity, forms the backbone of most economies, whether developing countries or highly industrialised nations. Because of the central role of energy in society, decisions about reducing greenhouse gas emissions in the energy sector are never made in isolation but interact with the need to make or keep energy affordable, minimise environmental and health impacts, and maintain security of supply.

Currently, fossil fuels provide about 80% of the total world energy supply. The roughly 1 billion people who live in developed countries consume about half of the total global energy supplied, whereas the 1 billion poorest people in developing countries consume only around 4%. Under non-mitigation scenarios, CO$_2$ emissions from energy supply would increase by over 50% by 2030. Even though conventional reserves will eventually peak, proven and probable reservoirs of oil and gas are enough to last for several more decades. Non-conventional reserves are available at higher cost of extraction. In addition, coal remains a cheap and abundant fuel. Scarcity of global supply alone, therefore, is very unlikely to drive a major change in energy supplies away from fossil fuels. (WGIII 1.3, 4.2, 4.3)

Mitigation options

Key technological options to reduce greenhouse gas emissions from energy supply (excluding transport, which we will discuss separately in a later section) include fuel switching, power plant and distribution efficiency; nuclear power, renewable energy, and carbon capture and storage.

All of these technologies are currently available or expected to be commercialised before 2030. None of these technologies will in itself make a major difference to emissions over the next few decades, but taken together they can deliver significant emissions reductions. (WGIII 4.3, 4.4, 11.3)

Fuel switching

Changing from coal to natural gas in electricity power plants produces up to 60% fewer CO$_2$ emissions per unit of energy produced. However, fuel switching is a one-off measure that cannot deliver further continued emissions reductions once the switch has been made. (WGIII 4.4)

Power plant and distribution efficiency

Supercritical pulversed-coal plants are more efficient than conventional sub-critical steam turbine plants. Combined heat and power plants deliver heat directly as well as electricity and, therefore, are more efficient (in terms of the total energy supplied for each tonne of coal or gas burnt) than electricity-only plants and have fewer conversion losses.

Increased use of superconducting cables, sensors, and rapid response controls could optimise electricity system performance and minimise transmission losses (which jointly account for about 10% of total losses in the energy supply chain). (WGIII 4.3, 4.4)
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*Nuclear power*
Increased use of nuclear power could displace some fossil-fuel–based power plants. Advanced nuclear power plants to be commercialised between 2010 and 2030 are expected to offer improved safety and efficiency compared with current ones. Overall, it is estimated that the share of nuclear energy in the total energy mix could increase from about 16% currently to 18%. Given the strong growth in overall energy demand, this would equate to roughly a doubling of nuclear energy generation globally by 2030. Safety, weapons proliferation, and the disposal of nuclear waste remain as constraints for the widespread use of nuclear power, and controversy remains about the cost assumptions in nuclear power generation. (WGIII 4.4)

*Renewable energy*
Renewable energy could provide heat (sustainably grown biomass, geothermal, and solar energy) or electricity (wind, solar, hydro, geothermal, and bioenergy), so could replace future fossil fuel power plants. Small-scale distributed renewable energy systems can offer added benefits of reduced transmission and distribution losses. Advanced renewable energy including power generation from wave and tidal energy and concentrated solar energy are only at the experimental stage but could become commercialised by 2030 (some researchers argue that concentrated solar power could be commercialised in the very near future). (WGIII 4.4)

*Carbon capture and storage*
The most recent technological development that could reduce CO\textsubscript{2} emissions from the power sector is the capture of CO\textsubscript{2} that is produced during combustion of fossil fuel, and its long-term storage in deep underground saline aquifers, disused oil and gas fields and coal seams, or in the deep ocean (for more details, see Special Report on Carbon Capture and Storage (IPCC, 2005)). At present, only the combination of carbon capture and storage with natural gas-fired power plants is at a stage where first demonstration projects are being developed; the combination with coal and biomass remains at the conceptual or experimental stage, but could become commercialised before 2030. Most of the barriers to carbon capture and storage appear to be economic and regulatory rather than technological challenges. (WGIII 4.3, 4.4)

*Economic potential, policies, and barriers*
Using the technologies described above to reduce greenhouse gas emissions generally imposes costs. Realising the total economic mitigation potential, therefore, requires policies that provide additional incentives for their implementation and address the current cost imbalance between carbon-intensive and low- or zero-carbon energy sources. Some of the policies that have been shown to be effective in supporting the introduction of these technologies include the reduction of existing fossil fuel subsidies,\textsuperscript{40} taxes, or other charges on fossil fuels based on their greenhouse gas emissions, minimum feed-in tariffs for small-scale renewable energy (ie, the ability to feed electricity produced by a single solar panel into the grid and be paid for this by power companies), renewable energy obligations for power companies, and producer subsidies. (WGIII 4.5)

\textsuperscript{40} Current government subsidies for the energy sector as a whole amount to about US$250 billion to US$300 billion per year globally, but only about 2–3% of these subsidies are directed at renewable energy. (WGIII 4.5)
One of the reasons it takes a long time particularly in the energy sector to reduce emissions (and hence why early action is particularly important) is the long lifetime of capital infrastructure. Only about 1–3% of existing power plants (and those in the process of being built) will be replaced in any given year over the next few decades. The diffusion of low-carbon technologies, therefore, is expected to take many decades even if early investments in such technologies are made attractive, particularly in developing countries where most of the new investment is expected to occur. This inertia in the power sector is one of the key reasons why mitigation actions are urgent, particularly where new power plants are being built, even though the stabilisation of greenhouse gas concentration is not expected to be achieved until, at best, the end of the 21st century. Chapter 8 looks in more detail at the implications of this inertia in the energy sector for actions that would be necessary to stabilise greenhouse gas concentrations at low levels. (WGIII 4.5)

Taking all options together, bottom-up studies estimate that at a cost of up to US$20/tCO$_2$-eq avoided, emissions from the energy supply sector could be reduced by 1.2–2.4 GtCO$_2$-eq per year in 2030 relative to what emissions would have been in the absence of such measures. At costs up to US$100/tCO$_2$-eq avoided, the economic mitigation potential increases to between 2.4–4.7 GtCO$_2$-eq per year. This potential is roughly evenly split between developing and developed countries, but with a greater potential in developing countries for the upper end of mitigation costs. (WGIII 4.3, 4.4, 11.3)

### 6.4.2 Buildings

The building sector includes residential and commercial buildings. It also includes the systems used to heat, cool, and light buildings, as well as the appliances used by occupants for the myriad of functions carried out in buildings. The sector offers the largest economic potential for low-cost mitigation (see also Figure 6.6), but also faces some of the largest barriers to achieving that potential.

In 2004, the building sector emitted approximately 14 GtCO$_2$-eq of greenhouse gases, including approximately 8.6 Gt of direct CO$_2$ emissions, 3 Gt of indirect CO$_2$ emissions from electricity generation, 1.5 GtCO$_2$-eq of F-gas emissions, and 0.5 GtCO$_2$-eq of CH$_4$ and N$_2$O emissions. By 2030, direct emissions of CO$_2$ are projected to grow to between 11.1 Gt (B2 scenario) and 14.3 Gt (A1B scenario), but F-gas emissions could be essentially eliminated. (WGIII 6.2, 6.3)

Emissions from the building sector come from three categories.

- Energy embodied in buildings.
- Energy consumed during the use of the building.
- Emissions of non-CO$_2$ gases (e.g., refrigeration, air conditioning, and insulation).

Building construction uses large amounts of steel, cement, glass, and so on. Techniques for reducing the amount of energy and greenhouse gas emissions from the production of these materials are discussed in the section on mitigation in the industry sector (section 6.4.3). However, there are also opportunities for reducing the amount of energy associated with building construction. For example, using local materials and materials that have fewer embedded greenhouse gas emissions, and

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41 F-gases are the gases hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride. These gases are produced synthetically and are used in a range of industrial applications as refrigerants and as insulators. They are included in the gases controlled by the Kyoto Protocol.
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minimising land clearance will reduce the overall emissions associated with building construction. (WGIII 6.3, 6.4)

About 1.6 billion people in developing nations do not have access to grid-based electricity, and hundreds of millions more have only limited access. Providing these people with adequate energy services is a necessary step in poverty alleviation. However, how these services are provided, whether from coal-based electricity generation or from renewable energy sources, will define a large part of future greenhouse gas emissions associated with the building sector. Options for reducing the carbon-intensity of energy supply have been discussed in the previous section; the remainder of this section focuses on options to reduce the energy consumed by and emissions of non-CO₂ gases from buildings.

**Energy efficiency**

Designing and operating buildings in the most energy efficient manner creates most of the potential for mitigation in the building sector. The principles involved are simple, and have been well demonstrated in many parts of the world. They include reducing heating, cooling, and lighting loads; using active solar energy and other environmental heat sources; increasing the efficiency of appliances, heating and cooling equipment, and ventilation; applying a systems approach to building design; and changing behaviour.

*Reducing heating, cooling, and lighting loads*

The thermal envelope of a building is its walls, windows, doors, insulation, and so on, everything that separates the inside of the building from the outside environment. Improved thermal envelopes can reduce heating loads by a factor of two to four compared with standard buildings. Advanced designs have reduced energy consumption by as much as 90% in cold-climate countries compared with buildings meeting national building codes in those countries. (WGIII 6.4)

The proper choice of building shape and orientation, the use of reflective materials for building surfaces, planting shade trees, and a variety of other design techniques can dramatically reduce cooling loads. Passive cooling techniques (eg, evaporative cooling and/or circulating cool night-time air through the building) can further reduce cooling loads.

Lighting loads can be reduced by enhanced use of daylight rather than artificial lighting and by using high-efficiency lighting systems. Conventional incandescent lights are only about 15% as efficient as compact fluorescent bulbs in providing light per unit of energy; LED (light-emitting diode) bulbs are about 1.5 times more effective than compact fluorescents. (WGIII 6.4)

*Using active solar energy and other environmental heat sources*

Solar thermal systems for domestic hot water are widely used in tropical and subtropical areas. Building roofs and other surfaces can be platforms for photovoltaic systems (ie, for solar panels that generate electricity). Water systems and air can be used as heat sources or sinks for heat pumps. Both heating and cooling loads can be reduced by using geothermal systems, which depend on the fact subsurface temperatures are closer to the annual average than surface temperatures. They circulate air or a heat-transfer fluid underground to cool it in the summer and heat it in the winter. (WGIII 6.4)
Increasing the efficiency of appliances, heating and cooling equipment, and ventilation

Household appliances, office equipment, and consumer electronics account for more than 40% of total residential primary energy demand and 70% of electricity demand in 11 large countries that are part of the Organisation for Economic Co-operation and Development (OECD). The most efficient appliances require a factor of two to five times less energy than the least efficient appliances. (WGIII 6.4)

Applying a systems approach to building design

Attention is usually paid to the energy efficiency of individual building components, but often little or no attention is paid to the interaction between these components or how they will be used once the building is completed. A systems approach (eg, ensuring that building heating and cooling equipment is adequate for the building’s size, and having an energy management system that ensures all components are used optimally) is needed to ensure that design energy efficiency will be achieved. The systems approach can be implemented by commissioning and using building management systems. Commissioning is a quality control process that includes design review, functional testing of energy-consuming systems and components, and clear documentation for the owners and operators. Building management systems establish procedures to ensure the continual monitoring of energy efficiency performance and control of operations and maintenance necessary for continued energy efficiency over the life of the building. Some progress has been made in implementing these approaches in commercial buildings but their extension to residential buildings remains a challenge. (WGIII 6.4, 6.7)

Changing behaviour

The best technological options are worthless if they are not used properly. Appropriate thermostat settings, turning off lights and appliances when not in use, ensuring doors and windows are closed in cold weather, and similar behaviours can significantly reduce building energy use. (WGIII 6.4, 6.7)

Mitigation potential and co-benefits

The AR4 found that as much as 29% (about 3.2 Gt) of global CO\textsubscript{2} emissions from the building sector projected for 2020 could be avoided at no net negative costs (ie, the energy savings alone outweigh the costs of mitigation measures). Another 3% of projected emissions could be avoided at costs up to US$20/tCO\textsubscript{2}, and another 4% for costs up to US$100/tCO\textsubscript{2}. The additional mitigation potential available at higher costs (US$20/tCO\textsubscript{2} and above) is very likely to be underestimated because most studies so far have focused only on the large low- (or net negative) cost potential. (WGIII 6.5)

Essentially, all of the low- and high-cost mitigation potential is available using currently available technologies. Application of these technologies would also provide a range of co-benefits, including reduced local and regional air pollution; improved health and quality of life; improved productivity in commercial buildings; the creation of employment and new business opportunities; improved social welfare and poverty alleviation; and improved energy security. (WGIII 6.6)

Barriers to implementation of mitigation options

Given the large potential for zero or net negative cost mitigation in the building sector, the obvious question is: why are these measures not being implemented? A key reason is that buildings are complex systems and until recently little thought
had been given to taking a systems approach in their design. The typical design is linear and sequential, designing the building shell first, and then the various building systems. Often the design process is fragmented, with different individuals or teams responsible for designing the shell and building systems with little communication and joint planning. Finally, the owner of a building may not be the occupier (this applies to both commercial and residential buildings), so that the energy savings or co-benefits of mitigation measures do not go to the person who would need to implement the mitigation measures in the first place. (WGIII 6.5, 6.6, 6.7)

The main barriers to the implementation of mitigation options in the building sector relate to the building’s orientation, shape, and design; investment cost; information; the cost of retrofits; and social factors.

**Building orientation, shape, and design**

Building orientation and shape are particularly critical issues, because of their impact on heating, cooling, and lighting loads. However, building orientation and shape are usually dictated by factors other than energy efficiency. To give a typical example: the traditional design for most multi-storey buildings uses interior stairwells, which will always require artificial lighting if the building has more than two floors. An external stairwell can use day-lighting, reducing energy demand. However, building owners have to accept the non-traditional design, convince architects of such a design, and possibly battle with building regulations. (WGIII 6.7)

**Investment cost**

Initial cost is another huge barrier. Energy efficient equipment may reduce costs over the life of a building, but it often has a higher capital cost. Particularly in the residential sector, buildings are designed and constructed by companies that will sell them as soon as they are completed. These companies have far larger incentives to minimise construction costs than to minimise lifetime costs. Even in the commercial sector, incentives are often misaligned. The building owner pays for the initial construction, but the tenants pay for energy use. Again, there are larger incentives for the building owner to minimise construction costs than to minimise lifetime costs. Both problems are aggravated if the building construction company has limited access to financing. (WGIII 6.7)

**Lack of information**

Lack of information also limits the use of available options. Building construction, particularly in the residential sectors, is often carried out by small companies or individuals who may not have access to good information about energy efficiency options. Even when they do have access to such information, they often lack the technical ability to understand it or the incentives to find architects and builders who will deliver energy efficient buildings. The highly fragmented nature of the building industry compounds this problem, since a builder must deal with many suppliers and subcontractors, who also often lack information or the ability to use it. (WGIII 6.7)

**Cost of retrofits**

The long lifetime of buildings is a major impediment to improving their energy efficiency. Some aspects of building design, for example, the building’s orientation, cannot be changed once the building is constructed. Other building features can be changed, for example, more energy efficient windows can be installed in older buildings or insulation can be upgraded, but the cost–benefit ratio for such
improvements is far less attractive than for incorporating energy efficiency features in the original building design. In many cases, mitigation options that have net negative costs in new buildings have significant costs as retrofits. Also, since retrofits usually involve a significant disruption in building use, building owners are often reluctant to undertake them even if there is a long-term cost saving. (WGIII 6.7)

**Social factors**
Lifestyle and cultural factors also complicate attempts to reduce building sector energy use. Increased living space is a sign of wealth in many countries. Where land is readily available, floor space per capita increases as the society becomes wealthier, even as family size decreases. All other factors being equal, larger houses use more energy than smaller ones. Cultural preferences affect many other aspects of building sector energy use. Cold water is traditionally used for clothes washing in China, whereas hot water is widely used in Europe and the United States. In New Zealand clothes are often dried outdoors, even by people who can easily afford a clothes drier, whereas in the United States drying clothes outdoors is considered a sign of poverty (in some suburbs, drying clothes outdoors is explicitly prohibited by by-laws). There are also wide disparities amongst relatively rich countries in preferences for amounts of indoor lighting, heating, and cooling and the socioeconomic status that is signalled by different choices. The so-called rebound effect can also limit the long-term effectiveness of energy efficiency measures: for example, the use of heat pumps for more effective space heating can increase the demand for your home to be warm in the morning before you get out of bed, or to leave the heating on when a room is unoccupied. Such behavioural responses can offset some of the efficiency gains, but there is considerable debate in the literature about how large this effect really is. (WGIII 6.7)

**Overcoming barriers to mitigation**
The above discussion of barriers to mitigation shows clearly why the market mitigation potential can be much smaller than the economic mitigation potential under current policies. However, the full economic mitigation potential could be realised if both a price on carbon and additional supporting policies are implemented. These additional policies include regulatory approaches; the provision of information; voluntary programmes; government leadership, and demand-side management programmes.

**Regulatory approaches**
Building codes and appliance efficiency standards are fundamental to ensuring a minimum level of energy efficiency in this sector. Appliance standards tend to be applied at the national or even international level, but building codes are often designed and always enforced at the local level. This can create problems since local authorities may lack the technical skill or support from their local community for such measures. (WGIII 6.7, 6.8)

Other regulations can also play an important part in improving energy efficiency in the building sector. The European Union Directive on the Energy Performance of Buildings (Directive 2002/91/EC) requires four major actions from member states (WGIII 6.8). Member states must:

- develop a common methodology, which may be differentiated at the regional level, for calculating the integrated energy performance of buildings
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- establish minimum standards for the energy performance of buildings, and require that renovated non-residential buildings meet the same standards as new buildings
- establish a certification scheme for new and existing buildings that makes information on the energy performance of buildings available to building tenants and buyers
- require regular inspection and assessment of boiler and heating and cooling systems.

Provision of information
For appliances, information barriers can be overcome with labelling programmes that state how much energy the appliance will use in a year or over its lifetime. Information barriers for buildings are harder to overcome. Labelling programmes, such as Energy STAR in the United States, provide overall evaluations for new buildings, but typically do not provide the detailed information needed for building buyers to compare buildings.

Energy audits, which are occasionally supported by government programmes or utility companies, provide information about opportunities to reduce energy use. The myriad of carbon footprint calculators available on the Internet also allows users to identify opportunities to reduce their own building energy use. (WGIII 6.8)

Voluntary programmes
Voluntary schemes such as the Leadership in Energy and Environmental Design (LEED) Programme developed by the Natural Resources Defense Council and administered by the United States Green Building Council is a comprehensive approach to designing sustainable buildings, which includes many aspects other than energy efficiency. The scheme has six standards and four levels of certification. More than 100 million square meters of building space in 30 countries are LEED certified. However, critics of the LEED approach complain that its standards do not recognise local conditions in its approach to sustainability, and that the cost of the verification and monitoring can be excessive. Another interesting voluntary effort was the One-Watt Challenge issued by the International Energy Agency to electronics managers to reduce standby power demand to no more than one watt. Many manufacturers had not considered this a design goal, but almost all were able to comply once confronted with the challenge. (WGIII 6.8)

Government leadership
In the United States, government agencies at many levels have established policies to build only LEED-certified buildings. Since 2005, United States government agencies are required to buy only Energy STAR rated appliances. Overall energy use per square metre in United States federal buildings has been reduced by 25% since 1985.

The European Union Directive on the Energy Performance of Buildings has special requirements for public buildings, and programmes requiring government purchase of energy efficient appliances are in place in China, several European Union countries, Japan, Korea, and Mexico. Such programmes provide important public leadership in improving building energy efficiency. (WGIII 6.8)
Demand-side management programmes
The United States Energy Policy Act 1992 mandated a rate structure for electric utilities that would make investments in energy savings as attractive as investments in new generating capacity. Implementation of this mandate has been mixed, but significant investments have been made, particularly in California and New England. For the industry as a whole, demand-side management investment has been estimated at 0.5% of revenues, with annual savings estimated at 1.9% of revenues. There is limited use of similar programmes elsewhere. In some countries, energy prices are either high enough to encourage reduced demand; in others, energy is subsidised, particularly for residential customers. (WGIII 6.8)

6.4.3 Industry
The industrial sector emits CO$_2$ as the result of fossil fuel combustion for heat and electricity, and from processes such as cement and lime manufacture. It also emits the full range of non-CO$_2$ greenhouse gases, including: hydrofluorocarbons such as HFC-23 from the production of HFC-22, a commonly used refrigerant; perfluorocarbons from aluminium smelting and semiconductor processing; sulphur hexafluoride from use in electrical switchgear and magnesium processing; and CH$_4$ and N$_2$O from a variety of chemical and food industry processes. Industrial CO$_2$ emissions have risen with the growth of industry globally, whilst non-CO$_2$ emissions have fallen as the result of mitigation measures, some of which were undertaken voluntarily. Total emissions from the industrial sector, including indirect emissions related to the generation and supply of electricity and steam from external power plants, were about 12 GtCO$_2$-eq in 2004. (WGIII 7.1)

Energy-related CO$_2$ emissions totalled almost 10 GtCO$_2$-eq in 2004. About 85% of these emissions came from six energy-intensive industries: iron and steel, non-ferrous metals, chemicals and fertilisers, petroleum refining, minerals (cement, lime, glass, and ceramics), and pulp and paper. Much of this industry is now in developing countries. In 2003, developing countries accounted for the production of 42% of iron and steel, 57% of nitrogen fertiliser, 78% of cement, and about 50% of primary aluminium. Energy-related CO$_2$ emissions are projected to rise to about 14 GtCO$_2$-eq in 2030 under the B2 SRES scenario, and to about 20 GtCO$_2$-eq under the A1B scenario. (WGIII 7.1)

Mitigation options
Mitigation options cover a wide range of categories; some can be applied across a whole sector, while others are process-specific: energy efficiency; fuel switching, including the use of waste materials; heat and power recovery; renewables; feedstock changes, including recycling; product changes; materials efficiency; control of non-CO$_2$ gases; and CO$_2$ capture and storage. Table 6.2 overviews some of the sector-wide and process-specific technologies in each of these categories. (WGIII 7.2, 7.3)

Energy efficiency
Both hardware and software approaches offer significant mitigation potential. Hardware approaches include the use high-efficiency, properly sized electric motors and appliances; the use of high-efficiency heaters and furnaces; the control of compressed air and steam leaks; and improved insulation. Software approaches include energy management systems and computer control of energy-using equipment.
Fuel switching, including the use of waste materials

Some industrial processes require specific fuels, for example, metallurgical coke for iron ore reduction in blast furnaces, but most processes use fuel for steam generation and process heat. Replacing coal with oil or natural gas, using CH\(_4\) from landfills, or using waste materials, for example, used oils, for fuel will reduce greenhouse gas emissions.

Heat and power recovery

Many industrial processes operate at high temperature and/or pressure, creating the potential to convert unused heat and pressure into steam or electricity, thus improving the overall efficiency of the process. Ammonia manufacture is one of the most efficient industrial processes, but even the best available ammonia plants use 50% more energy than the thermodynamic minimum (i.e., the amount of energy that basic laws of physics indicate are necessary to create ammonia). Most industrial processes operate at lower efficiency and thus have more waste heat available.

Renewables

Industrial processes that are based on biomass, for example, pulp and paper, have a long history of using biomass waste for energy. Other industries have used biomass fuels, for example, iron smelting used charcoal in Brazil until the 1990s. Industry uses electricity from wind and solar energy when it is available, and proposals have been made to use concentrated solar energy as a source of industrial process heat.

Feedstock changes, including recycling

Recycling significantly lowers greenhouse gas emissions in the aluminium and glass industries. Most studies show that paper recycling reduces greenhouse gas emissions, but results are highly dependent on study assumptions. Some industries can reduce emissions by changing feedstock, for example, using blast furnace slag in cement production.

Product changes

Product changes can reduce greenhouse gas emissions in manufacture (e.g., replacing low-strength steel with a smaller amount of high-strength steel) or in end-use (e.g., replacing cast iron with aluminium or ceramics to reduce the weight, and, therefore, the fuel consumption, of automotive engines).

Materials efficiency

Thinner containers use less aluminium or glass than thicker containers, so have lower greenhouse gas emissions from their production.

Control of non-CO\(_2\) gases

N\(_2\)O emissions from chemical processes (e.g., nylon manufacture) can be eliminated by thermal oxidation. Emissions of hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride can be controlled by process changes to eliminate their emission or use, or by capture and destruction. CH\(_4\) can be burned as fuel instead of being emitted.

Carbon capture and storage

The manufacture of hydrogen, which is carried out on a large scale for petroleum refining and ammonia production, produces a high-concentration CO\(_2\) by-product stream. This eliminates the need for the ‘capture’ portion of carbon capture and storage, the most expensive part of this technology. Other processes’ steams
(eg, blast furnace top gas) contain higher concentrations of CO\textsubscript{2} than power plant flue gas, and are early candidates for carbon capture and storage.

**Economic potential, policies and barriers**

In contrast to the mitigation options in the building sector, most of the industrial mitigation options do impose additional costs. The amount of mitigation that can be achieved in the industry sector, therefore, depends on the costs we are prepared to accept for mitigation. The AR4 estimated that, assuming the B2 SRES scenario as a baseline scenario and at costs up to US$100/tCO\textsubscript{2}-eq, the industry sector mitigation potential was 2.0–5.1 GtCO\textsubscript{2}-eq (about 10–30% of the projected emissions) in 2030. (WGIII 7.5)

There are two main barriers to achieving this potential. (WGIII 7.6)

- Many developed and developing nations lack clear mitigation requirements. Individual companies may implement mitigation options to meet their sustainable development goals or to reduce costs, but these benefits alone will not ensure widespread adoption of mitigation technology. (WGIII 7.6, 7.9)

- Developing nations lack technical and financial resources and access to information, particularly for small and medium-sized enterprises. Several programmes under the United Nations Framework Convention on Climate Change aim to provide support for the transfer of clean technology to, and financial support for mitigation efforts in, developing countries, but these programmes have not yet led to widespread access or adoption of industrial mitigation technology. (WGIII 7.6, 7.9)

Governments have a large range of policy options available to encourage or require mitigation in the industrial sector. These options include carbon taxes, cap-and-trade systems, emission standards, information programmes, and voluntary agreements. All are being implemented in various countries to meet Kyoto Protocol targets. A price on carbon or other financial incentives are generally necessary (but not sufficient) to make the widespread adoption of mitigation options cost-effective for industry. (WGIII 7.6, 7.9, 11.4, 11.5)

A key barrier to implementing a price on carbon in many countries is the concern about loss of competitiveness for domestic industries resulting from such an additional cost within a global market place. An interesting approach being considered for future climate agreements to reduce this barrier is sectoral emission targets. Under this approach, emissions targets would be set for industries globally rather than for individual countries. The benefit of this approach is that it would minimise concerns about international competitiveness, since all competitors in a given industry would be subject to the same target. However, there are both technical and political barriers to this approach. The major technical barrier is that, for most industries, technology is highly varied and target setting would be a very complicated process. The major political barrier is that industry accounts for no more than a third of total greenhouse gas emissions in most countries. Sectoral targets would have to be coupled with other policy approaches to ensure the deep reductions in greenhouse gas emissions necessary to stabilise atmospheric concentrations of greenhouse gases. In addition, domestic subsidies and regulatory advantages provided to specific industry sectors could further reduce the benefits of global sectoral targets. Chapter 10 discusses in more detail the key processes and challenges involved in future climate agreements. (WGIII 7.7, 7.9, 7.12, 13.2, 13.3)
### Table 6.2: Sector-wide and process-specific mitigation options for industry

<table>
<thead>
<tr>
<th>Sector</th>
<th>Energy efficiency</th>
<th>Fuel switching</th>
<th>Power recovery</th>
<th>Renewables</th>
<th>CO2 sequestration</th>
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<th>O2-use, hydrogen</th>
<th>CO2 separation, from flue gas</th>
<th>O2-use, biomass</th>
<th>Biomass, PV</th>
<th>Wind turbines, hydropower</th>
<th>O2-use, SR</th>
<th>O2-use, electrolysis</th>
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<th>O2-use, solar</th>
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Notes: BF = blast furnace; CO$_2$ = carbon dioxide; CFCs = chlorofluorocarbons; CH$_4$ = methane; GHG = greenhouse gas; HFCs = hydrofluorocarbons; HVAC = heating, ventilating, and air conditioning; n.a = not applicable; N$_2$O = nitrous oxide; O$_2$ = oxygen; PFCs = perfluorocarbons; PV = photovoltaics; SF$_6$ = sulphur hexafluoride. Technologies in italics are not yet commercially available but under demonstration or development.

Source: WGIII Table 7.5.
6.4.4 Combining forces – reducing greenhouse gas emissions from electricity

Electricity is one of the most convenient modes of delivering energy, because it is flexible and virtually pollution-free at the point where it is used. However, annual emissions from the production of electricity in fossil-fuel–fired power plants currently contribute more than half of the total greenhouse gas emissions produced through energy supply and consumed mainly by buildings and industry. Emissions from electricity supply have risen strongly over the past few decades at a global scale and are projected to increase further, from about 9 GtCO$_2$-eq in 2000 to more than 16 GtCO$_2$-eq in 2030. (WGIII 4.2, 4.4)

Figure 6.7 shows that this emissions growth could be halted and even reversed by the combination of improved energy efficiencies in buildings and industry and a reduced carbon intensity of electricity supply. Each of the available mitigation options takes only a small ‘wedge’ out of the projected emissions growth; none of the options is itself sufficient. However, if we were to take all these options together and apply them globally, greenhouse gas emissions from electricity generation in 2030 could be reduced by about 15% relative to 2000, rather than increased by almost 80%. These potential emissions reductions are based on the economic mitigation potential in power supply, buildings, and industry for emission reduction costs up to US$50/tCO$_2$-eq, and assuming mid-range scenarios for emissions growth in the absence of mitigation measures. Achieving this mitigation potential would require policies that result in an effective price on CO$_2$ emissions, as well as other measures to remove barriers to the implementation of mitigation options in buildings and industry. (WGIII 4.4, 4.5, 6.6, 6.7, 6.8, 7.5, 7.6, 7.9)

**Figure 6.7:** Effect of combined mitigation options in reducing emissions from the electricity sector, 2000–2030

Note: CCS = carbon capture and storage. The figure shows the combined economic mitigation potentials from buildings, industry, and energy supply for the global electricity sector between 2000 and 2030, relative to baseline growth in the absence of mitigation measures.

Source: Based on WGIII Figures 4.29 and 4.30, data in WGIII 4.4, Table 4.6, 6.7, 7.5.
Reducing the Pressure: Potential for mitigation

Note that one of the most substantial options to reduce greenhouse gas emissions from the transport sector, without requiring a complete restructuring of transport systems, is the shift to electrically powered vehicles (see also section 6.4.5). If this shift were to occur on a large scale, it would place additional demand on electricity supply and could reduce the fraction of electricity that can be supplied from renewable sources, or in turn require additional renewable electricity generation to meet this demand.

6.4.5 Transport
Mitigation in the transport sector presents serious challenges: almost total dependence on a single, carbon-intensive energy source, rapid growth in emissions, and projections of continued demand growth.

Most of the emissions from the transport sector come from the burning of fossil fuels (about 95% in the form of petroleum). In 2004, the transport sector emitted 6.3 GtCO$_2$, which was 23% of the world’s total energy-related CO$_2$ emissions. From 1971 to 2000, transport CO$_2$ emissions nearly doubled, which was the highest growth rate of any end-use sector. The transport sector also emits small amounts of CH$_4$ and N$_2$O from combustion, and F-gases from automotive air conditioners. Data on non-CO$_2$ emissions is available only from the European Union, Japan, and United States, and there is high variability between the three locations especially for the contribution from F-gases associated with air conditioning. (WGIII 5.2)

World transport energy use is projected to grow by 2% per year over the next few decades (about 1.2–1.3% per year in OECD countries and 3% per year or more in emerging economies), leading to an increase of about 80% between 2000 and 2030. Light-duty vehicles are projected to account for 38% of the transport energy demand growth; freight trucks, 27%; and air travel, 23%. With few exceptions, light-duty vehicle ownership correlates well with national GDP per capita, so as personal income rises, vehicle ownership and transport emissions can be expected to rise. Global vehicle ownership, therefore, is projected to triple between 2000 and 2030, with most growth occurring in non-OECD countries (see Figure 6.8). Petroleum is projected to continue to supply the bulk (93–95%) of transport energy in 2030; CO$_2$ emissions from transport, therefore, are expected to grow at the same rate as transport energy demand (from 6.3 GtCO$_2$ to 11.4 GtCO$_2$ per year from 2000 to 2030) unless dedicated mitigation policies lead to fundamental shifts in transport technology and fuels. (WGIII 5.2)

Mitigation options – efficiency improvements
Three techniques can provide small-to-moderate reductions particularly in light-duty vehicle CO$_2$ emissions (most are also applicable to buses and trucks): improved efficiency of vehicle engine and transmission systems, reducing vehicle load, and hybrid engine systems. Reductions are also possible in aviation. (WGIII 5.3)

Improved efficiency of engine and transmission systems
A turbocharged, direct-injection Mercedes gasoline engine reduces fuel consumption by 18% compared with its conventional counterpart, whilst a direct injection diesel engine is 35% more fuel efficient than its conventional counterpart. Improved transmissions reduce fuel consumption by 4–8%. Computer control of engine operation, which is now standard on most new vehicles, can also more closely match engine operation to vehicle energy needs.
Figure 6.8: Vehicle ownership as a function of per capita income for a range of countries

Note: Continuous lines show changes in subsequent recent years (years for individual countries vary, with the last year generally being 2003).
Source: WGIII Figure 5.2.

Reducing vehicle load
Using light-weight materials (aluminium, high-strength steel, and plastics), improving vehicle aerodynamics, using low-resistance tyres, and improving the efficiency of vehicle accessories, such as air conditioners, will lower fuel consumption. All of these techniques are in use, but additional gains, particularly from weight reduction through the use of composite materials, could still be substantial.

Hybrid engine systems
Hybrids combine a fuel-driven internal combustion engine with an electric engine system consisting of an electric motor or generator, and a battery for energy storage. Conventional hybrids, which are commercially available, recharge the battery with regenerative breaking and engine charging. Hybrids save fuel by:

- stopping the internal combustion engine whenever it is not needed (including during braking and coasting)
- recovering braking losses and storing the recovered energy in the battery
- using the electric motor to boost power during acceleration, allowing internal combustion engine downsizing
- using the electric motor during low load, the least efficient portion of internal combustion engine operation
- shifting accessory operation to electricity.

The benefits of hybrid operation are most evident in city driving with its frequent short-term acceleration, braking, and low load operation. Overall, conventional hybrids, which use all of the above techniques for fuel savings, are 40–50% more efficient than their non-hybrid counterparts in a combined city–highway cycle.
Hybrids account for only a small fraction of the global vehicle fleet. Their further penetration into the fleet would lead to substantial fuel savings.

**Aviation sector improvements**
Efficiency improvements are also possible in the aviation sector through improvements in engine and aircraft design (about 20% by 2015 and 40–50% by 2050) and the use of alternative fuels, including biofuel mixes. Changing flight altitudes and routes could also contribute to reducing CO₂ emissions, but could interact with the formation of high-altitude clouds (contrails) and the chemistry of the ozone layer, so that the benefits and trade-offs of altered flying routes have large uncertainties with regard to their climate benefits. (WGIII 5.3)

**Mitigation options – fundamental changes in fuels and their sources**
Three approaches appear to offer deep emissions reductions that go beyond the marginal efficiency improvements listed above: electrification of road transport using low or non-carbon sources of electricity, hydrogen fuel cells operating on low- or non-carbon hydrogen, and biofuels. However, as discussed in Box 6.2, the greenhouse gas emissions reduction potential of biofuels and their sustainability significantly depends on the raw material from which the biofuel is produced, which could limit the quantity that can be commercially made available on a global scale over the next few decades.

**Electric cars**
A first step towards electrification is the plug-in hybrid, which uses a larger battery than the conventional hybrid and can be recharged from the grid. These vehicles are capable of travelling moderate distances, up to 200 km, on battery alone, but may still have an internal combustion engine to recharge the battery or power the vehicle when the battery is depleted. Plug-in hybrids are expected to be commercialised in 2010 or soon thereafter. (WGIII 5.3)

The climatic benefits of plug-in hybrids depend on the source of electricity and the range of the vehicle on battery alone. A recently published life-cycle assessment comparing non-hybrid vehicles, conventional hybrids, and plug-in hybrids showed that using United States average greenhouse gas emission factors for electricity generation, plug-in hybrids offered a 32% reduction in emissions compared with non-hybrid vehicles, but only a 5% reduction in emissions compared with conventional hybrid vehicles. However, using a low-carbon mix of electricity generation (ie, mainly from renewable resources), plug-in hybrids would offer a 50–65% reduction in emissions compared with non-hybrid vehicles and a 25–40% reduction compared with conventional hybrids. (Samaras and Meisterling, 2008; also WGIII 5.3)

Current battery technology limits electric vehicles to a short range of some 100–200 km or light, limited-capacity operations. Battery technology has been extensively researched for many decades, making a fundamental breakthrough in the near future unlikely. Large-scale use of electric vehicles over the next two decades, therefore, would probably require a battery exchange scheme that would allow drivers to quickly replace discharged batteries with fully charged ones, analogous to filling an empty fuel tank, or widely available public rapid battery-charging stations. Both approaches are being explored.
**Hydrogen-powered cars**

Hydrogen fuel cells for automotive use are under development at many locations. They are a highly efficient way of generating electricity, but their greenhouse gas emission reduction potential depends on the source of the hydrogen. Most hydrogen is produced by gasification of fossil fuels with emission of the by-product CO\textsubscript{2}. This method of hydrogen production offers only a small greenhouse gas emission benefit over a hybrid car, even when the fossil fuel is natural gas (but it does offer a substantial co-benefit in terms of reduced local air pollution). However, if the by-product CO\textsubscript{2} is captured and stored, a hydrogen fuel cell could reduce vehicle life-cycle CO\textsubscript{2} emissions to very low levels. An alternative is to use sustainably grown biomass for hydrogen production coupled with carbon capture and storage. In this case, CO\textsubscript{2} emissions could even be negative; that is, more carbon is removed from the atmosphere by growing the biomass than is emitted through the life cycle. However, the increases in non-CO\textsubscript{2} gases, particularly N\textsubscript{2}O, from the large-scale production of biofuels would have to be considered. Finally, hydrogen can be produced by electrolysis of water using low-carbon electricity, or by high temperature dissociation in a nuclear reactor. In these cases, hydrogen fuel cell vehicles could have very low life-cycle CO\textsubscript{2} emissions. (WGIII 5.3)

**Biofuels**

Biofuels produced from sustainably grown biomass would also decarbonise the transport sector, because in principle the biomass removes CO\textsubscript{2} from the atmosphere as it grows, so CO\textsubscript{2} emissions caused when the biofuel is burnt do not increase the net CO\textsubscript{2} content of the atmosphere. However, this simple picture does not necessarily hold in practice, because the net mitigation potential depends significantly on the raw material from which the biofuel is to be produced, how this raw material is produced, and what other land use the production of the raw material replaces (see Box 6.2).

At present, sugar cane represents the only commercially competitive source for biofuels that also leads to significant reductions compared with fossil fuels in an analysis that accounts for all emissions that occur in the production of the biofuel crop, its processing, distribution and final use. Biofuels from cellulosic waste products also offer significant life-cycle emissions reductions but are currently much more expensive on a global scale than the fossil fuels they compete with. By contrast, the emissions reductions from biofuels derived from corn and other grains are much smaller than from sugar cane. These biofuels can even lead to increased emissions once global changes in land use resulting from changing crop prices and the emissions associated with this land-use change are fully taken into account (WGIII 5.3; Searchinger et al, 2008; Tollefson, 2009).

A recent study suggested that converting biomass into electricity for subsequent use by electric cars produced significantly more kilometres travelled per area of cropland and higher emissions reductions than if biomass were converted into ethanol for use in cars with combustion engines (Campbell et al, 2009). This highlights the possible link between alternative strategies for achieving large-scale reductions in greenhouse gas emissions from transport.

There are numerous other questions about the use of biofuels for transportation, including the effects that it has on food prices and the impact that large-scale biomass cultivation for fuel would have on biodiversity and food security. These topics are discussed in Box 6.2.
Reducing the Pressure: Potential for mitigation

One approach to generating biomass for conversion to biofuels that appears to reduce sustainability concerns and offers net emissions reductions is the intensive cultivation of algae in tanks. Algae grown naturally on ponds could be a sustainable source of biomass, but is not economically attractive because it requires a large surface area and the algae grow slowly. However, algae grown on artificial surfaces in tanks, using power plant flue gas as a source of higher concentration CO₂ could have significant potential (Avro, 2009).

**Modal switches, transport infrastructure improvements, and land-use planning**

Car-pooling, using public transportation, and using non-motorised transport reduces the number of vehicle kilometres travelled, so reduces fuel use and CO₂ emissions, as well as reducing local air pollution and traffic congestion. These approaches are well established in many places around the world, but their introduction in new locations often meets a high level of social resistance and may involve substantial up-front capital costs (such as the installation or upgrading of light rail transport systems). (WGIII 5.3)

A wide variation exists between countries of the share of non-motorised transport. Apart from reflecting social and cultural attitudes to alternative transport options, urban design and safety are generally seen as key aspects that can support non-motorised transport. The long lifetime of urban infrastructure indicates that while changes in non-motorised transport share are difficult to implement rapidly, early action is required if longer-term shifts are to be achieved. (WGIII 5.3)

Improving roads and traffic control systems offers a short-term benefit in CO₂ emissions as a result of reduced traffic congestion, but this benefit often disappears with time as it invites more vehicles to use the road. Land-use planning that reduces the amount of travel needed to commute to work, for shopping, and so on can also reduce vehicle use. Due to their contingency on social acceptance, it is generally difficult to quantify the emissions reductions that can be realistically achieved or the economic mitigation potential from modal switches (see also section 6.4). (WGIII 5.3)

**Mitigation potential, costs, policies, and barriers**

Most studies of economic mitigation potential and costs relate only to specific technologies, sectors, and countries, and most exclude, for example, the widespread commercialisation of electric vehicles before 2030. Based on those narrow assumptions, the AR4 estimated the total economic mitigation potential for light-duty vehicles to be 369–697 MtCO₂ at net negative costs, about 700 MtCO₂ at carbon prices up to US$20/tCO₂, and about 740 MtCO₂ for carbon prices up to US$100/tCO₂. For aviation, the mitigation potential is estimated at 150 MtCO₂ at carbon prices less than US$50/tCO₂ and 280 MtCO₂ at carbon prices up to US$100/tCO₂. Estimates of the economic mitigation potential of biofuels in the transport sector vary widely, from 600 MtCO₂ to 1,500 MtCO₂ at costs up to US$25/tCO₂. (WGIII 5.4)

In total, available studies for the three main sectors building, industry, and transport suggest a total mitigation potential of 1,600–2,550 MtCO₂ at carbon prices up to US$100/tCO₂. This potential is only a small fraction of the sector’s estimated total emissions of some 16 GtCO₂ in 2030. (WGIII 5.4)

It should be noted that the economic mitigation potential estimated above excludes options for improved efficiency of rail transport, heavy-duty road transport, or shipping. It also excludes possible reductions in travel demand arising from changes in urban design or consumer preferences, or resulting from policies...
dedicated to promoting shifts towards more public or non-motorised transport, because no reliable estimates of the costs and potential of these options currently exist on a global scale. Fundamental technology leaps and large-scale shifts in consumer attitudes with regard to accelerated introduction of electric vehicles and battery storage could further accelerate the development and diffusion of lower-emissions transport options, but the feasibility and costs of increased uptake in this technology are equally difficult to assess with confidence. (WGIII 5.3, 5.4)

The steep cost curve for technological mitigation options indicates that, apart from a significant fraction of zero-cost options, further improvements all tend to come at relatively high costs. Countries with historically higher fuel taxes have shown consistently lower emissions per vehicle kilometre travelled and lower rates of car ownership, but these measures have not been sufficient to halt the growth in transport emissions in virtually all developed and developing countries. Due to the relatively high costs of further technological mitigation options, carbon prices alone seem to be insufficient to maximise emissions reductions in the transport sector. Additional policies would be necessary to mobilise emissions reductions that rely mostly on consumer choices (such as driving behaviour, demand patterns, and consumer attitudes to various types of car) that do not readily translate into monetary costs but rather reflect wider societal attitudes. Many countries have implemented compulsory labelling for carbon emissions and fuel efficiency to encourage the purchase of more efficient cars, in addition to minimum fuel efficiency standards for car manufacturers. In addition, urban design that can actively support low-carbon transport and social mobility is promoted in many countries, but often with only soft or diffuse targets. Mandatory biofuel targets have also been used to accelerate the uptake of biofuels and ensure technological compatibility of engine design with new fuels blends. However, recent concerns about the sustainability and life-cycle assessment of biofuels have required re-adjustments or more careful requirements in biofuels policies (WGIII 5.3, 5.4, 5.5; Harrabin, 2008; Tollefson, 2009).

6.4.6 Agriculture

Since the 1960s, the total land area under agriculture has increased by about 10% (with an almost 20% increase in developing countries and a 2% decrease in developed countries). Agricultural production has also grown on a per hectare basis, so total agricultural production has more than kept pace with the world’s growing population: world population has grown by about 100% since the 1960s, but per capita food supply has increased by about 9% (energy and protein) in developed countries and 31% for energy and 123% for protein in developing countries. The growing demand for food has been met through technological innovations and improved practices, but has also increased pressure on the environment through the increased use of energy, fertilisers, herbicides, and pesticides and the release of greenhouse gases.

Most greenhouse gas emissions from agriculture are non-CO\(_2\) gases, CH\(_4\) and N\(_2\)O. CH\(_4\) is produced when organic material decays without oxygen being present; the main human-induced activities contributing to such emissions are enteric fermentation (the digestive process of ruminant animals), rice production, and the decay of animal manure. N\(_2\)O is produced by the microbial transformation of nitrogen compounds in fertilisers, soils, and manure, particularly where available nitrogen exceeds the amount that can be taken up by plants. CO\(_2\)-eq emissions of CH\(_4\) and N\(_2\)O combined in 2005 are estimated at 5.1–6.1 GtCO\(_2\)-eq, about 10–12%
of total anthropogenic greenhouse gas emissions. Agricultural CH\textsubscript{4} and N\textsubscript{2}O constituted about 50% and 60% of total anthropogenic CH\textsubscript{4} and N\textsubscript{2}O emissions, respectively (the remainder of CH\textsubscript{4} comes from fossil fuels and waste and of N\textsubscript{2}O from industrial processes). Emissions of CH\textsubscript{4} and N\textsubscript{2}O increased by about 17% from 1990 to 2005, with a 32% increase in developing countries and steady emissions or even declines in most OECD countries. (WGIII 8.3)

Agriculture also produces large flows of CO\textsubscript{2} to and from the atmosphere through its uptake and release by soils, animals, and plants. However, the net flux to the atmosphere is believed to be currently small and constitutes less than 1% of total anthropogenic CO\textsubscript{2} emissions. As we will see, this does not mean that mitigation options related to CO\textsubscript{2} are also minor: since agriculture is responsible for large fluxes both to and from soils, increased uptake of CO\textsubscript{2} by soils can make a significant contribution to reducing net CO\textsubscript{2} emissions (ie, by creating carbon sinks). CO\textsubscript{2} is also emitted through energy consumed in agricultural practices and processing, but these emissions and their mitigation options are generally included in the relevant other sectors such as transport, buildings, and industry. (WGIII 8.3, 8.4)

Projections of future emissions from agriculture vary and need to take into account regional population changes, shifts in diet, and changes in agricultural practices. Estimates for 2030 suggest global emissions could rise from currently about 6 GtCO\textsubscript{2}-eq (CH\textsubscript{4} and N\textsubscript{2}O) to 8.0–8.4 GtCO\textsubscript{2}-eq, which is an increase of 33–40%. Almost all of this growth is expected to occur in developing regions. Energy consumption (cropland management, irrigation) is also expected to increase. (WGIII 8.3)

**Mitigation options**

In contrast to most other sectors, the options of reducing greenhouse gas emissions through agriculture do not lie only in reducing direct emissions caused by agricultural activities. Net global emissions can also be reduced by enhancing the uptake of CO\textsubscript{2} in agricultural soils and by producing biofuels that can replace fossil fuels. Estimates of the net result on global greenhouse gas emissions typically have much greater uncertainties for agriculture than for industrial processes, energy supply, transport, or buildings due to the reliance on complex and interconnected biological systems (which, in turn, also depend on climate conditions).

**Land management**

Soil carbon stored in crop and grazing lands can be enhanced through using improved crop varieties and grasses, extending crop rotations and planting alternative species, reduced or zero tillage, and managing crop residues. Nutrient management (ie, optimal use of fertilisers and use of nitrogen-fixing plants) can also make important contributions to reducing N\textsubscript{2}O emissions. The draining of peat lands for agricultural productions leads to very large emissions of N\textsubscript{2}O and CO\textsubscript{2}. Avoiding and reversing such drainage constitutes a significant mitigation option. Restoration of degraded agricultural lands to lands with permanent vegetation cover can also increase carbon storage both above and below ground. Use of irrigation can improve soil carbon storage and avoid land degradation, but its net effect depends on energy consumed for irrigation processes, and can lead to increased N\textsubscript{2}O emissions. CH\textsubscript{4} emissions from rice cultivation can be reduced by short-term draining of paddies, the use of higher yield varieties, the off-season management of paddies, and the use of residues. (WGIII 8.4)
Livestock and manure management

CH$_4$ emissions from livestock can be reduced by feeding livestock more concentrated food, increasing productivity per animal, using specific CH$_4$-suppressing feed additives, changing herd structures, and selective breeding. Many of these options have important trade-offs, such as consumer resistance to feed additives, gains in productivity per unit of product being offset by increased total outputs, and interactions between changes in herd structures and selective breeding with animal fertility and other farm management practices. CH$_4$ emissions from animal manure can be reduced by various management options such as separating solid and liquid fractions, biogas collection, composting, and storage and treatment. The release of N$_2$O when manure is spread on grazing and crop lands can be reduced, similarly to emissions from other nitrogen-based fertilisers, by adjusting amounts and timing to optimise uptake by plants. (WGIII 8.4)

Biomass for bioenergy production

As already noted in section 6.4.5 (biofuels for transport), the climate benefits of biofuels depend significantly on the specific type of biomass used to produce the biofuel, its management, and the vegetation cover and land use that it replaces. Plant waste material produced as a by-product of agricultural food production can provide suitable biomass for biofuels that is sustainable and offers significant co-benefits, but at present the cost of such fuels is much higher than fossil fuels. Some dedicated crops, such as sugar cane and switchgrass, also tend to offer net greenhouse gas benefits and can be produced at moderate costs, while biofuels produced from corn may even lead to significant net emissions increases once global changes in land use are taken into account (WGIII 8.4). For a more detailed discussion of the sustainability of biofuels, see Box 6.2.

Mitigation potential, policies, and barriers

The feasibility, effectiveness, and cost of any of the above mitigation options depend significantly on local conditions in which agricultural production occurs. The variety of soils, crops, climatic conditions, other environmental constraints, and financial and technical capacity of farmers to adopt and implement mitigation options varies hugely across the world.

With these caveats and uncertainties in mind, the global economic mitigation potential in 2030 excluding biofuels is estimated at 1.5–1.6 GtCO$_2$-eq for carbon prices of US$20/tCO$_2$-eq, 2.5–2.7 GtCO$_2$-eq for carbon prices up to US$50/tCO$_2$-eq, and 4.0–4.3 GtCO$_2$-eq for carbon prices up to US$100/tCO$_2$-eq. About 70% of this potential lies in developing countries, 20% in OECD countries, and the remaining 10% in countries in eastern Europe with economies in transition. These estimates include soil carbon management options but do not include options to reduce energy-related CO$_2$ emissions. Almost 90% of the total mitigation potential is estimated to be in the form of increased soil carbon storage, about 9% in reduced CH$_4$ emissions, and 2% in reduced N$_2$O emissions from soils. (WGIII 8.4)

Biofuels are estimated to be able to replace fossil fuels and thus avoid emissions of up to 0.07–1.3 GtCO$_2$-eq for carbon prices of US$20/tCO$_2$-eq, and 0.6–2.3 GtCO$_2$-eq for carbon prices up to US$50/tCO$_2$-eq. The wide range of these estimates reflects the different net benefits of alternative biofuels and their biomass sources, as well as uncertainties in accounting for their net benefit at the global scale (see section 6.4.5 and Box 6.2). (WGIII 8.4)
At the lower end of carbon prices, the most effective mitigation options in the area of land and livestock management are those that are consistent with current practices and have co-benefits in terms of reduced energy or fertiliser costs, improved productivity, or reduced other environmental impacts. At higher prices, other options such as changes in land use and land restoration, biofuel production from sustainable sources and cellulosic materials, and animal-feed–based options become more competitive. (WGIII 8.4, 8.6)

A key barrier to measures to reduce agricultural net emissions for almost any carbon price is that much of the mitigation potential exists in developing countries where per capita incomes of farmers are low. The implementation of uniform carbon prices in the order of tens of United States dollars per tonne of CO$_2$-eq emitted or avoided would not be compatible with many local economies and the overriding requirement to ensure food security and sustainable livelihoods. Policies aimed at reducing emissions from agriculture, therefore, have to be integrated into wider sustainable development policies that are consistent with local social, economic, and environmental contexts. While such policies can be effective in realising the economic mitigation potential at low costs (including those that may have net negative costs), they are unlikely to bring about mitigation that involves real and substantial costs to farmers who earn only a couple of dollars per day. Non-climate policies (such as agricultural subsidies, tariffs, economic structures, and environmental constraints) can also have a larger impact on agricultural greenhouse gas emissions than any current climate policies, which emphasises the need to integrate mitigation efforts into a broader policy environment. Other constraints on the effective implementation of climate policies can include the small size of individual holdings and resulting difficulty in achieving economies of scale, the cost and uncertainty in monitoring and verification of mitigation measures, and transaction costs for small-holders under incentive-based policies. (WGIII 8.6, 8.7)

Even though increased soil carbon storage shows the largest mitigation potential, it has the disadvantage that it may not be permanent but subsequent reversals in land management or in climate could release some of this CO$_2$ again and thus reverse or reduce the initial gains. However, not all agricultural mitigation options suffer from this potential impermanence; for example, emissions of N$_2$O and CH$_4$ that have been avoided, or the substitution of fossil fuels with biofuels, constitute permanent benefits to the atmosphere. (WGIII 8.6)

This discussion shows that agriculture has a significant potential to reduce net greenhouse gas emissions, and some of the mitigation options could have significant co-benefits. However, realising this potential represents significant challenges for policy especially in developing countries due to the interaction of agriculture with such fundamental demands as food security and creating sustainable rural livelihoods within an increasingly global trade of food and biofuels. Virtually all mitigation options discussed in this section are currently available and are being practised in some form. However, technological research and development of new mitigation options are also important, particularly to reduce costs at the upper end of the range, improve effectiveness, reduce uncertainties and barriers to implementation, and ensure compatibility with farm management practices in different regions. Technological options are particularly important to tackle areas of future high emissions growth where mitigation options are currently limited, including those related to an increasing shift towards meat-based diets in some regions. (WGIII 8.9, 8.10)
Box 6.2: Biofuels – opportunities and challenges in a global context

Replacing fossil fuels with biofuels is attractive because it requires little change in the technology or processes that use this fuel. In principle, the carbon dioxide (CO$_2$) emissions from biofuels when they are burnt are carbon neutral because they would have absorbed this same amount of CO$_2$ when the original plant material grew. However, several issues make this simple picture rather more complicated in practice.

First, the cultivation of biomass and its conversion into biofuels leads to emissions of CO$_2$, methane (CH$_4$), and nitrous oxide (N$_2$O). These emissions arise from soil tillage and fertilisation or cultivation of algae, energy used in processing raw materials, along with fermentation and other chemical reactions to generate the final biofuels with higher energy density than the raw products. Emission factors for CO$_2$ and CH$_4$ in these processes are reasonably well known, but emission factors for N$_2$O are still a subject of considerable debate. Since N$_2$O is a powerful greenhouse gas, a small change in its emissions factor can have a significant effect on the attractiveness of biofuels as a mitigation strategy. In principle, these emissions can be accounted for in simple life-cycle assessments, but the total amount of emissions that biofuels avoid compared with fossil fuels becomes less certain and depends on the specific way (land management, fertiliser inputs, irrigation) in which the biofuel was produced (Delucchi and Lipman, 2003; Wu et al, 2006; Crutzen et al, 2007; Börjesson, 2009).

A further complicating factor is that land is not in unlimited supply. The overall emissions balance of biofuels, therefore, also depends on what alternative form of land use has been or is being replaced by biofuel cultivation. Growing biofuels on marginal agricultural land has much greater emissions benefits than if virgin forest is cleared to produce palm oil; some studies suggest that if native forest is cleared to create space for palm oil plantations, it may take 80–90 years of biofuel production to create real benefits in terms of reduced carbon emissions compared with the use of fossil fuels. Apart from the high direct emissions resulting from forest clearance, such land-use changes can also imply significant loss of biodiversity (Danielsen et al, 2008; Sheil et al, 2009).

The global trade in food and fuels means it is not possible to assess the trade-off between different land uses only for a specific region, because the consequences could be global. If the prices for biofuels go up globally, agricultural production might be shifted globally towards less productive soils. This in turn would require more fertiliser to produce the same amount of food, so the emissions from agriculture could be increased globally as a result of increased biofuel production (Searchinger et al, 2008). Using algae as a biomass source avoids, but does not necessarily eliminate, many of these problems, depending on the specific locations and scale at which algae are grown (Avro, 2009).

Biofuel plantations do not have exclusively negative side effects. Well-designed and well-managed biofuel plantations can offer important rural employment opportunities and provide an important source of foreign exchange for poor communities. They can also help retain biodiversity and manage water and nutrient run-off (particularly if the alternatives are unsustainable practices such as slash-and-burn agriculture). The social and biodiversity implications of biofuel production, therefore, are highly dependent on their local implementation. (WGIII 9.7, 12.3)
These issues are subject to considerable controversy. At the bottom of this debate often lies the fact that generalisations are not possible. The specific greenhouse gas emissions balance depends very much on the specific plants grown to produce biofuels, assumptions about how they are grown (eg, what fertiliser is used), and what alternative land uses these biofuel plantations compete with. Studies that account for the global shift in agricultural production as a result of increased biofuel plantations tend to give a much more negative view of the climatic benefits of biofuels. In particular, the use of grains (particularly corn) as a source of biofuels seems to result in a net increase in global greenhouse gas emissions once the effect of increasing corn prices and the resulting shifts in land use globally are taken into account. Biofuels produced from agricultural or forest cellulosic waste products have a much higher promise of offering real climate benefits (as well as other co-benefits) but tend to be more expensive at present. For other sources, such a sugarcane or switchgrass, their global emissions balance depends largely on the alternative land uses that would be possible in any given location. Various governments that had set mandatory biofuel standards have recently revised their criteria that biofuels have to meet in order to be regarded as sustainable and offering true net emissions reductions (Harrabin, 2008; Charles, 2009; Tollefson, 2009).

Apart from the potentially limited climatic benefit of some biofuels, high food prices during 2007 and 2008 highlighted that biofuels can also act in direct competition with agricultural food production and thus threaten food security, especially in poor regions. The causes of high food prices are complex, but are thought to be a combination of production remaining below average due to droughts in some key regions, low stocks and increased use of agricultural commodities in investment markets, and increasing demand for biofuels. The latter contributed not so much through a direct competition for land, but high oil prices led to higher prices for biofuels (including those derived from grains in the United States market), which in turn drove up the global price for corn and other grains that provide essential food resources for billions of people. About half of the increased demand for coarse grains and vegetable oil over recent years has come from the increased demand for biofuels (OECD, 2008b; Tangermann, 2008). Apart from their direct impact on food prices, increased global demand for biofuels could also increase the power of large land-holdings to achieve economies of scale in biofuel production, which in turn could increase pressure on small farmers and rural communities (Eide, 2009). These studies suggest that, in the longer term, a substantial increase in global demand for biofuels can be met sustainably only if most of those biofuels are produced from agricultural or forest waste materials (so-called ‘second generation’ biofuels) rather than from primary agricultural food stocks.

6.4.7 Forests
Similar to agriculture, forestry can potentially play multiple roles in the mitigation of greenhouse gas emissions. Wood products meet many essential human needs for fuel and construction materials but are generally associated with the release of CO₂ to the atmosphere, either immediately (if wood is burnt) or over the longer term (if wood is used as a tool or building material that then eventually decays over periods of years to many decades). (WGIII 9.2)

Emissions of CO₂ from deforestation made up about 17% of global total CO₂-eq emissions in 2004 (about 8.3 GtCO₂-eq), which made it one of the largest sectors
contributing to anthropogenic (human-induced) greenhouse gas emissions. Large uncertainties are associated with any global or even regional estimates of emissions from deforestation due to the difficulty of measuring such carbon fluxes directly and accurately over large areas. Apart from emissions resulting from the burning or decay of wood, carbon stored in soils is also released when forests are cut and land is converted from forest to agricultural land. Year-to-year variations in climate conditions (especially El Niño events) can also lead to large inter-annual variability in emissions from forest areas around the world. (WGIII 9.3)

Most deforestation is currently occurring in tropical and subtropical regions, where the harvest of such forests provides income, land for agriculture, and fuel. At the same time, afforestation and enhanced growth of forests, mainly in temperate and northern regions, can absorb additional carbon from the atmosphere and thus offer an additional sink. The positive effect of afforestation is already included in the estimate of 8.3 GtCO₂-eq net emissions from forestry globally. Figure 6.9 shows the estimated regional trends in CO₂ emissions associated with forestry since about 1850. (WGIII 9.3)

Even though the sum of anthropogenic activities related to forestry (ie, deforestation, forest degradation, afforestation, and forest management) is a large net source of carbon, it should be noted that the terrestrial biosphere as a whole acts as a net sink of carbon, that is, it absorbs more carbon than it releases. This is because all plants all over the globe also respond indirectly to human activities and natural variations such as increasing CO₂ concentrations in the atmosphere, longer growing seasons in temperate and high latitudes, and in some regions forests are recovering and regrowing naturally after human or natural past disturbances. This overall global terrestrial carbon is currently absorbing a significant fraction of CO₂ emitted from the burning of fossil fuels, but this sink is expected to decrease over time as the climate continues to warm (see chapters 3 and 4). It is also difficult to manage directly. The discussion in this chapter focuses only on those human activities that can have a direct influence on greenhouse gas emissions from forests: reducing deforestation, increasing afforestation, and increasing carbon storage through forest management. Further options consist of using forests to produce biofuels that can replace fossil fuels or finding ways to extend the lifetime of harvested wood products to delay the release of their carbon to the atmosphere. (WGI 7.2, 7.3; WGIII 9.2, 9.3)
Figure 6.9: Regional trends in emissions and sinks from forest-related activities since the 1850s

Note: The figure shows regional estimated trends in carbon dioxide (CO$_2$) emissions (in megatonnes of CO$_2$ per year) from forest-related activities since the 1850s. Data are averaged for five-year periods. Source: WGIII Figure 9.2.
Mitigation options, policies, and barriers

Assessing the options to reduce net emissions from global forestry needs to account for not only direct emissions, but also the interactions of forestry with other sectors. This includes interaction with other types of land use (e.g., the possible expansion of forest land at the expense of food production or the shift of food production towards more emissions-intensive practices), and the emissions implications of substitution between wood products and alternative non-renewable materials (e.g., cement, aluminium, and steel instead of wood for building materials, or fossil fuels instead of wood-derived biofuels). Figure 6.10 illustrates these interactions schematically.

Eliminating wood entirely from its uses in human society would generally mean that the functions and services previously offered by wood (fuel, tools, construction material) are fulfilled by non-renewable alternative materials such as fossil fuels or other (mostly carbon-intensive) building materials. The challenge for mitigation options, therefore, is to find ways to meet human needs while minimising net emissions of greenhouse gases to the atmosphere through sustainable forest harvests and reducing unsustainable resource use. (WGIII 9.1, 9.4)

Figure 6.10: Relationship between forest sector and other land uses and land-use services

Minimise net emissions to the atmosphere

Maximise carbon stocks

Non-forest land use

Forest ecosystems

Biofuel

Wood products

Fossil fuels

Other products

Land-use sector

Forest sector

Services used by society

Note: The figure illustrates the interaction of forest-specific mitigation options in the context of the overall goal of minimising net emissions of greenhouse gases to the atmosphere.

Source: Based on WII Figure 9.3.

In general, mitigation options can be grouped into four broad areas: maintaining and increasing forest area by reducing or avoiding deforestation and increasing afforestation; increasing the density of carbon within forest stands through forest management; increasing the density of forests across landscapes and increasing their resilience against pests and disturbances such as wildfires; and maximising the amount of carbon stored in construction and replacing fossil fuels with wood-derived biofuels. The latter option reduces net emissions to the atmosphere by avoiding the emission of fossil fuels or by enhancing the removal of CO₂ from the atmosphere followed by CO₂ storage in long-lived materials.

Issues surrounding reducing deforestation and increasing afforestation are discussed in detail below. (WGIII 9.4)
Reducing deforestation

Deforestation in tropical countries is the largest source of CO$_2$ emissions from forestry, so reducing its rate would offer the largest short-term benefits. While there are large uncertainties, most studies agree that deforestation would remain high over coming decades in the absence of dedicated climate policies, leading to, for example, the elimination of as much as 40% of the total Amazon forest cover by 2050. (WGIII 9.4)

The key challenge for climate policies is to understand and counteract the drivers for this deforestation, which are difficult to generalise. Clearing forests can be driven by the value of timber, local fuel demand, or the value of land for agriculture or alternative planted forest species. Even though retaining existing native forests can have large co-benefits in terms of preventing soil erosion, maintaining biodiversity, and tourism opportunities, non-climate policies have had very limited success in preventing further deforestation. (WGIII 9.6)

The cost of avoiding deforestation is largely determined by the value that the forest owner derives from clearing the forest, that is, by the value of timber sold or by the value of land that has become available for alternative uses (agriculture, urban development, biofuel production). Simply prohibiting further deforestation, therefore, is not a feasible option in general, since it would entail real and significant costs (in terms of foregone earnings or livelihoods) for people involved in deforestation. However, a key problem in reducing deforestation is that the main climatic value, the avoided emission of CO$_2$, is not seen by local land-owners, so does not enter their balance sheet. Current international climate policies under the United Nations Framework Convention on Climate Change (UNFCCC) provide no incentives for developing countries to reduce deforestation. Part of the difficulties lie in the fact that countries or individual farmers would need to be compensated for not clearing forests, rather than for concrete actions such as planting new forests. Uncertainty about baselines (i.e., how much forest would have been cleared without climate policies, and what total CO$_2$ emissions would this have represented) have acted as barriers to implementing policies that would recognise and compensate for the value of avoided carbon emissions. Current negotiations under the UNFCCC are trying to address this gap and to ensure that future policies can implement a price signal for carbon emissions from deforestation and thus can offer a financial reward for countries and land-owners who forego the financial benefits of clearing forests for timber or alternative land uses. The limited abilities of some developing countries to implement and administer such policies will remain though. (WGIII 9.4, 9.6).

Increasing afforestation

The counter to avoiding deforestation is increasing afforestation. The net carbon benefits of afforestation depend significantly on the land use before afforestation; land with high soil carbon content could lose more carbon from soils than accumulates in trees, while plantations on degraded and marginal agricultural land are more effective. If new forests are planted for eventual harvest, the use of the harvested wood determines whether the carbon stored in wood is released immediately back to the atmosphere (e.g., if used for firewood) or only over periods of decades to centuries (e.g., if used in house construction).

The determinants of the cost of afforestation activities are the return on timber (if the forest is to be harvested in future) and the value of land for alternative uses. The costs of afforestation as a mitigation measure, therefore, are highly dependent on specific regions, tree species, and non-climate policies that influence returns from
timber and from agriculture, which represents the main alternative land use for forest areas. (WGIII 9.4, 9.6)

**Economic mitigation potential**

Assuming that policies that recognise the value of carbon stored in forests and their soils are implemented globally, what is the total mitigation potential from forestry at a range of costs? Estimates that provide answers to this question cover a wide range. This range reflects uncertainties about baselines (eg, what would be the rate of deforestation and afforestation in the absence of climate policies – which in turn depends on the expected value of timber and the value of agricultural products that could be grown on the same land) as well as different methods to estimate the potential. (WGIII 9.4)

At costs up to US$100/tCO$_2$-eq, regional bottom-up studies estimate that the combination of all forestry mitigation options globally (excluding biofuels) can provide an economic mitigation potential of 1.3–4.2 GtCO$_2$-eq in 2030. About 50% of this potential exists at much smaller costs up to US$20/tCO$_2$-eq, and most of this low-cost potential exists in developing countries through avoided deforestation. Top-down estimates tend to give much higher potentials for a given cost than regional bottom-up assessments, of 13.8 GtCO$_2$-eq at costs up to US$100/tCO$_2$-eq. (See section 6.3.1 for an explanation of ‘bottom-up’ and ‘top-down studies.) Differences between top-down and bottom-up estimates probably arise from the fact bottom-up assessments are better able to account for region-, climate-, and species-specific constraints or opportunities associated with required land-use changes. Even though different bottom-up studies use different approaches and cover different regions, the aggregated bottom-up estimate is generally seen as more reliable (but also more conservative) than the larger top-down estimates. (WGIII 9.4)

The above figures for the mitigation potential from forestry exclude the potential production of biofuels from planted forests. Several issues make it difficult to establish accurately the mitigation potential from biofuels: the carbon balance of biofuels depends not only on the carbon absorbed by trees but also on changes in soil carbon that may occur over time. It crucially is also influenced by the question of what land use the plantation of biofuels replaced. For example, if rainforests are cleared to make space for biofuel plantations, this could lead to net emissions to the atmosphere, even if those biofuels then are used to replace fossil fuels for many years. However, the feed stock for biofuels can also play an important role in the overall emissions balance (for some recent perspectives on this, see, for example, Danielsen et al, 2008; Börjesson, 2009; Sheil et al, 2009; Thamsiriroj and Murphy, 2009). Biofuels from forestry thus face similar general problems as biofuels produced by agriculture, although their emissions are somewhat easier to account for due to the more limited emissions of non-CO$_2$ gases (CH$_4$ and N$_2$O) in forestry plantations (see sections 6.4.5 and 6.4.6, and Box 6.2). Available studies suggest that biofuels derived from planted forests have an economic mitigation potential of 1.3–4.2 GtCO$_2$-eq at costs up to US$100/tCO$_2$-eq. The potential of forestry to provide biofuels has been included in the relevant sector where those biofuels would be used (mainly transport, see section 6.4.5) when the total global economic mitigation potential was derived. (WGIII 9.4, 11.3)

A challenge for all forestry-related climate policies is that the climatic benefit (ie, the accumulation of carbon from the atmosphere into wood) occurs only slowly over several decades, whereas the release of carbon to the atmosphere often occurs within a very short interval when trees are felled and soils are disturbed. Protecting
Reducing the Pressure: Potential for Mitigation

forests for climate reasons, therefore, generally requires a relatively large up-front investment and incentives to land- and forest-owners not to make use of the short-term returns that the felling of trees and land conversion can offer. Similarly, forest management options that increase carbon storage in individual stands or that increase the density of forests across landscapes take many years to accumulate their carbon benefits but incur ongoing costs. Policies that can provide payment for the carbon that is being accumulated (or whose release is avoided), therefore, are essential to ensure full use is made of forestry as mitigation option. (WGIII 9.4, 9.6)

6.4.8 Waste

Consumer waste is the smallest sector contributing to human greenhouse gas emissions. In 2005, total emissions from waste were estimated at about 1.3 GtCO$_2$-eq or less than 3% of all anthropogenic emissions. Waste-related emissions come mainly in the form of CH$_4$ from landfills, with smaller contributions of CH$_4$ and N$_2$O from wastewater, and CO$_2$ from waste incineration of fossil-carbon derived products. Incineration of organic waste (ie, material derived from plants or animals) is not assumed to lead to any net CO$_2$ emissions to the atmosphere since plant material would have absorbed the equivalent amount of CO$_2$ from the atmosphere when it grew. Uncertainties for estimates of emissions from waste are relatively large due to inconsistent data sets and, in some developing countries, lack of consistent approaches to waste management that allow robust estimates of waste-related greenhouse gas emissions. Emissions from waste are expected to increase mainly in developing countries as their societies adopt Western lifestyles, which involve higher levels of consumption of goods, packaging, and managed waste disposal. Globally, emissions of landfill gas, therefore, are expected to almost triple between 2005 and 2030. Even though most of the growth in waste-related emissions is expected to come from developing countries, it is noteworthy that developed countries are responsible for about 50% of the total waste (measured as carbon) stored in landfills (see Figure 6.11). (WGIII 10.2, 10.3).

Figure 6.11: Estimated annual rates of carbon placed in landfills, in megatonnes of carbon, in different world regions, 1971–2002

Source: WGIII Figure 10.3b.
Despite the small size of the sector, waste management can provide effective mechanisms to reduce greenhouse gas emissions because only a limited number of stakeholders is involved. The key mitigation options include landfill gas recovery, improved landfill management practices, and wastewater engineering. Emissions can also be reduced by composting organic waste, incineration (thus avoiding the generation of CH$_4$ under anaerobic conditions and emitting the carbon in the form of CO$_2$ instead). Reducing the volume of waste through recycling, reduced packaging, and energy efficiency in waste management are also important opportunities. Many of these options offer strong co-benefits through the production of energy from landfill gas, reduced waste volumes, and associated management and resource demands, and reduced pollution. (WGIII 10.4, 10.6)

The global economic mitigation potential to reduce landfill gas emissions is estimated at up to 1 GtCO$_2$-eq at costs up to US$100/tCO$_2$-eq, which would offset 70% of projected emissions. Consistent with the large co-benefits of waste reduction options, 20–30% of this potential could be achieved at net negative costs, and 30–50% at costs up to US$20/tCO$_2$-eq. These estimates do not include all mitigation options for wastewater management. At the upper end of costs, advanced technologies for waste incineration and waste-to-energy conversion become viable. The costs and benefits of recycling are difficult to measure since they require a complete life-cycle assessment of the energy involved or avoided in the production of goods as well as the processes involved in recycling. Nonetheless, many countries have implemented widespread recycling schemes for their multiple co-benefits and because of their citizens’ increasing resistance to new landfills. (WGIII 10.4)

The implementation of options to reduce landfill gas emissions often requires a high initial investment followed by longer-term returns. Key barriers to realising the mitigation potential from waste, therefore, are mainly the lack of local capital in developing countries. The Clean Development Mechanism under the UNFCCC (see chapter 10) has been effective in addressing such constraints in some developing countries. However, the selection of locally appropriate technologies remains a challenge to ensure waste management options are sustainable in the face of rapidly growing and developing societies. (WGIII 10.5, 10.6)

### 6.5 Policies to support mitigation

The preceding sections found substantial economic potential across many different sectors to offset the projected growth of greenhouse gas emissions by 2030, or even reduce emissions below current levels, using technologies that are currently available or projected to be commercialised over the coming decades. However, the market potential for mitigation is generally smaller than the economic potential (see section 6.2). The full economic mitigation potential, therefore, is very unlikely to become a reality unless it is supported with adequate additional policies and barriers to its implementation are removed.

A wide variety of policies are available to governments to create incentives to implement mitigation measures that would not be used otherwise. Key criteria for any policy include its environmental effectiveness (does it achieve emission reductions?), its cost-effectiveness (are there alternative and cheaper ways of achieving the same goal?), its distributional effects (are the costs spread appropriately across society?), and its institutional feasibility (can the policy be implemented and administered?). (WGIII 13.2)
6.5.1 Role of a price on carbon

One crucial element of many mitigation policies is that they place an implicit or explicit price on greenhouse gas emissions, or that they reward financially the avoidance of such emissions and thus provide incentives for investments in cleaner (more efficient) products, processes, and services. An effective price signal could make many of the necessary additional investments into low-greenhouse gas emitting products, technologies, and processes that we discussed in the preceding sections more attractive. Conversely, in the absence of an effective cost associated with greenhouse gas emissions, incentives to reduce or avoid emissions beyond those situations where additional costs are offset by their co-benefits (e.g., from reduced energy costs) remain very limited. (WGIII 4.5, 6.6, 6.7, 7.9, 7.10, 11.4, 11.5)

We need to be clear though that a carbon price alone is unlikely to turn the full economic mitigation potential into a reality. As shown in the building sector, the fact emissions could be reduced in a way that is cost-effective to society as a whole does not mean the emissions reductions are cost-effective for the individuals or corporates that would have to take the specific actions. In addition, barriers can exist in the form of institutional arrangements, lack of information, and behavioural and cultural resistance against emissions reductions even where they have been made cost-effective (see Box 6.3 for examples of what carbon prices mean in everyday life). Comprehensive climate policies, therefore, generally use a portfolio of approaches that provide an implicit or explicit price for greenhouse gas emissions as well as additional measures to overcome specific barriers and achieve emissions reductions where price signals are not sufficient. (WGIII 4.1, 5.5, 6.7)

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**Box 6.3: Carbon prices and what they mean in everyday life**

It is worthwhile investigating the relative scale of carbon prices on the goods and services that one may use in everyday life, and to give some perspective to the abstract notion of figures such as $30/tCO₂-eq or $100/tCO₂-eq.

Each litre of petrol used in road transport produces about 2.4 kg CO₂ once it is burnt. This means a carbon tax of $30/tCO₂-eq would increase petrol prices by about 7 cents per litre.

Coal-fired power plants produce electricity at a cost of about US$20–50 per megawatt-hour (MWh) and release about 800–1,400 kgCO₂/MWh electricity depending on the technology and type of coal used. For a carbon price of US$30/tCO₂-eq, the cost of generating electricity produced from coal, therefore, would increase by about US$24–42/MWh or almost double.

Gas-fired power plants produce electricity at costs around US$40–50/MWh but release only about 400–500 kgCO₂/MWh electricity. A carbon tax of US$30/tCO₂-eq would thus increase the electricity generation cost by about US$12/MWh or about 25%.

By comparison, the cost of wind-generated electricity is about US$40–120/MWh depending on location and technology. This makes wind-generated electricity barely competitive against coal and natural gas in most countries. Placing a price of about US$30/tCO₂-eq on emissions would raise the cost of fossil-fuel-generated electricity and make wind more widely competitive and attractive. (WGIII Figures 4.19, 4.27, Table 4.7)
The significant increases in electricity generation cost for coal and gas would not translate into an equal increase in costs to consumers because the latter consists not only of generating costs (which in the United States constitute about one-third to one-half of the delivered cost of electricity) but also capital investments, electricity distribution and plant maintenance, and taxes and subsidies. The overall increase in electricity prices would also depend on the current and projected mix of coal, gas, oil, nuclear, and renewables in the current and future electricity generation system. Use of excess heat in combined heat and power systems would further reduce the relative cost increase per unit of energy (electricity and heat) supplied.

### 6.5.2 Portfolio of mitigation policies

Experience shows that there are advantages and disadvantages for any given approach; which approach is most appropriate will often depend on specific circumstances, and often the solution may be a combination of policies. In addition, it is worth remembering that any policy can be designed well or poorly, and can apply stringent or lax standards of compliance. Mitigation policies, therefore, can be assessed only at a general level, and individual instances of implementation and effectiveness may differ. The next paragraphs discuss some of the key findings on seven types of mitigation policies, based on recent experiences, their use in other environmental contexts, and theoretical analyses. (WGIII 13.2)

#### Taxes and charges

Taxes and charges on greenhouse gas emissions are the most direct and, in general, economically effective, way of providing incentives to reduce or avoid such emissions. Because the price for each tonne of greenhouse gas emissions is fixed, taxes and charges provide greater certainty about overall economic costs but cannot guarantee a particular emissions level, because some sectors of the economy may choose to pay the increased costs of emissions rather than reduce emissions by investing in more efficient technologies. Placing a tax on emissions is also referred to as ‘internalising’ the costs of greenhouse gases (ie, ensuring that the people or activities that release greenhouse gases and thus contribute to the global long-term damages from climate change are faced with the cost of those damages). In practice, the tax placed on greenhouse gas emissions does not necessarily equal the cost of damages from climate change, which is only poorly known (we discuss this at length in chapter 8). The main effect of a tax on emissions, therefore, is that it provides a direct economic incentive to reduce emissions as long as the cost of doing so (eg, through investing in new technology) is not greater than the tax value of the emissions that would be avoided.

#### Tradable permits

 Tradable permits (also known as cap-and-trade systems) are in some sense the opposite approach to taxes. For tradable permits, the government sets the total allowable amount of greenhouse gas emissions from a sector (or the entire economy), and allocates permits to individual emitters (often individual large companies) for the

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42 In this context, economically effective means that mitigation measures taken in response to carbon taxes are expected to result in the least cost across the economy for a given amount of emissions reduction.
emission of greenhouse gases up to the total allowed amount. If an individual emitter finds they are likely to exceed their allowance, they can invest in more efficient technology to reduce their emissions or purchase an allowance from another emitter who has managed to stay below their allowance.

Competition for emission permits creates an effective market price: if technological options to reduce emissions are cheap, then many emitters will aim to reduce their own emissions and thus the market price of additional emission permits will sink. If technological options are expensive, then emitters will seek to buy additional permits and the price of emission permits will increase. This process fixes the total amount of greenhouse gas emissions across the economy but leaves it to the market to determine the overall cost of reducing emissions. Fluctuations in the market price of permits, which is open to speculation just as any other financial market, can make it difficult to estimate the total cost across the economy to comply with emission caps. The way in which permits are allocated (e.g., through auctioning or by governments giving away some permits for free to reduce the direct cost on specific industry sectors) can be an intensely political process and can also impact on the price stability of carbon markets (Carbon Trust, 2009).

**Regulations and standards**

Regulations and standards generally require that products or processes adhere to minimum levels of energy efficiency, or that they incorporate a minimum of efficient or low-emitting technologies (such as minimal quota for renewable energy in the portfolio of large power companies). Such approaches can deliver some certainty about future emission levels and may be preferable when producers or consumers are unlikely to respond to direct price signals from taxes or tradable permits (such as in the case of energy efficiency measures in buildings, see section 6.4.2). Because regulations generally set fixed performance expectations based on the best available technologies, they are not as effective as taxes and permits in driving technological innovation. Also, once a standard is set, there can be considerable inertia in revising this standard even though the efficiency of available technology may have improved further.

**Financial incentives**

Governments often use financial incentives in the form of subsidies and tax credits to stimulate not only the development but also the early implementation of new technologies (including support for technology demonstration projects or reducing regulatory costs). Such incentives are often crucial to overcome barriers because they represent a reward rather than a financially punitive measure, even though they are typically less effective from a purely economic point of view. Financial incentives can also be used to encourage mitigation measures where taxes and permits meet market barriers; for example, in the area of buildings, financial incentives can be provided to building owners to implement energy efficient heating, cooling, and design options.

**Research and development**

Research and development and the subsequent demonstration and deployment of new technologies are an important part of reducing the long-term costs of reducing greenhouse gas emissions and enabling progress towards meeting more stringent emission targets. Apart from funding research and development, and the deployment of new technologies through subsidies and tax credits, governments can also stimulate such efforts by direct funding and by providing a supportive regulatory environment.
Voluntary agreements between industry and governments

Voluntary agreements between industry and governments to limit emissions or develop new technologies have played a major role in the development of many national-level climate policies because they overcome barriers by raising awareness and are politically attractive.

On their own, few voluntary agreements have achieved significant emission reductions beyond those reductions that would have occurred anyway. Voluntary agreements, therefore, are often seen as most effective if they are part of a coordinated package of measures. The most successful agreements are characterised by clear goals and baseline scenarios, the involvement of a third party in the design and review of standards and achievements, and formal provisions for monitoring progress towards the agreed targets.

Information

Information (eg, through awareness campaigns) is an important ingredient in the implementation of any policy measure. Even in the absence of additional policies, the availability of information about energy efficiency and greenhouse gas emissions associated with specific products and services is crucial for more informed consumer choices and can stimulate behavioural changes. There is little evidence about their actual impact on emissions.

Implementation of policies at national and local scales

In principle, all of the above policies can be (and many have been) implemented not only by governments but also by corporations and local and regional authorities. Non-governmental organisations and civil groups can also contribute and implement some of those options, with the exception of regulatory approaches and taxes or emissions caps. Actions by actors other than central government can make important contributions to mitigation by stimulating and testing innovative policies and encouraging the deployment of new technologies. They may limit greenhouse gas emissions within their specific sphere of influence, but their effect on national or regional level emissions is generally limited. (WGIII 13.4)

A common feature of all climate policies is that they are generally easier to implement when they are integrated into broader development objectives. For example, the introduction of feed-in tariffs or minimal standards for renewable energy is generally more productive and encounters fewer barriers if such measures are implemented while a country’s electricity sector is undergoing a wider restructuring process (eg, to enhance overall competitiveness) than if such measures are developed and introduced in isolation. (WGIII 12.1, 12.2, 13.2)

Taxes, tradable permits, and to some extent regulations also require effective monitoring and report mechanisms, to ensure the quantity of greenhouse gases that is emitted (or the energy used) can be compared with the emissions permits that a user holds, and that taxes can be levied according to actual emissions, and to enforce compliance with regulations. The IPCC has developed, at the request of the United Nations, extensive manuals for the monitoring and reporting of greenhouse gas emissions from a large number of sector-specific activities. In addition, many national and international industry bodies have developed their own additional sector-specific reporting guidelines.
6.6 Behaviour and lifestyle choices

The options to reduce greenhouse gas emissions discussed so far all focus on the use of existing or new technologies or processes to essentially deliver the same products or services, but at a lower level of greenhouse gas emissions. This is only one way of looking at the challenge of reducing emissions: another way would be to ask whether we want the specific product or service in the first place, and whether processes could be managed in fundamentally different ways to avoid greenhouse gas emissions. What differences can management, behaviour, and lifestyle choices make?

The scientific literature is surprisingly sparse on quantitative analysis of the effectiveness and potential of behavioural choices in reducing greenhouse gas emissions. This is in part because the potential to reduce emissions by not purchasing or using specific goods or services is difficult to quantify in objective terms and often includes subjective gains or losses in terms of health, lifestyle, and social and cultural values. Placing a cost on avoiding emissions in such a way would require us to take social and environmental co-benefits and trade-offs into account, which are notoriously difficult to measure and inevitably controversial.\(^{43}\)

In democratic societies, regulation is not generally an effective way to enforce behavioural changes due to the core value of personal freedom; on the other hand, once a sufficiently large number of people are embracing certain behavioural norms, they can become at least as binding and effective as regulation. Good examples for this are the gradual shift against smoking in many Western societies, the wearing of seat belts, and alcohol limits while driving. Breaching these norms is no longer a misdemeanour but regarded almost as a moral deficiency. However, development of public support and acceptance for changes in behavioural norms often requires a long period of public awareness raising, and inevitably lobbying by vested interests to retain the status quo, before this shift occurs on a sufficiently large scale to make a real difference.

With regard to greenhouse gas emissions and energy use, it is well recognised that education and training programmes can help overcome barriers to the market acceptance of energy efficiency measures. Occupant behaviour in buildings, which is often determined by sociocultural patterns rather than economic criteria, and education programmes and improved management can result in considerable reductions in energy-related emissions.\(^{44}\) Transport demand management can influence choices regarding the demand for and mode of transport (public, private, motorised or not), which can support greenhouse gas mitigation. In industry, staff

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\(^{43}\) For example, the technological way of reducing emissions from transport is to purchase a more fuel-efficient car. The behavioural way to reduce transport emissions is, for example, to take a bicycle, which can cut emissions by 100% rather than offer only marginal improvements. The problem is that, apart from being practical in only a limited number of circumstances, such a proposal is extremely value-laden in many societies. Based on my own experience in different parts of the world, riding a bicycle can be culturally associated with anything from ‘unsafe and degrading’ to ‘healthy and empowering’. Societal norms also influence perceptions whether, for example, riding a bicycle to work or participating in car-pooling schemes are regarded as an inconvenience (compared with use of a private car) or an opportunity to, for example, improve one’s fitness or maintain social networks. Objective statistical data on safety, health, and travel times using different modes of transport hardly ever fully justify such attitudes but typically reflect values and beliefs that are embedded deeply within societies.

\(^{44}\) For example, it is not an economic but rather a cultural decision whether room temperatures are adjusted to what is considered appropriate clothing, or whether clothing is adjusted to match room temperatures that have been set considering energy efficiency and environmental impacts.
training, reward systems, regular feedback, and documentation of existing practices can help overcome organisational barriers. (WGIII 4.1, 4.5, 5.1, 5.6, 6.7, 7.3)

On the basis of the limited current literature, behaviour, management, lifestyle, and consumption choices clearly can contribute to greenhouse gas emission reductions. The IPCC has not quantified the effectiveness and sustainability of reducing emissions through shifts in behaviours and lifestyles because of the conceptual difficulties outlined above and the resulting scarcity of quantitative peer-reviewed scientific studies.

Opinions in the scientific (and even more the popular) literature are divided regarding the real-world mitigation potential of behaviour changes. Their estimated long-term potential often depends on assumptions about current and future core values that will or should drive behaviours and lifestyle choices, and the assumed presence or absence of a moral mandate to create behavioural changes within societies where the majority shows a clear disinclination to such changes.

It might also be worth noting that changes in lifestyle for the sake of reducing greenhouse gas emissions could have unintended international side effects. The IPCC has not assessed these, but they appear relevant for this discussion. For example, abstaining from long-distance holiday travel to reduce greenhouse gas emissions could have a devastating effect on developing countries whose main source of income (and, therefore, access to technology and finance to manage their own greenhouse gas emissions or adapt to the impacts of climate change) are tourist flows. Environmentally conscious travel choices or gloomy predictions of the impact of rising sea levels could spell the demise of some Pacific island nations faster than rising sea levels themselves, despite the undoubted impact that climate change will have on these islands (Mortreux and Barnett, 2009).

A similar issue arises with supermarkets’ increasing efforts to source local produce and avoid imported foods due to the carbon emissions associated particularly with air freight: while this may appear as a good principle, more careful analysis shows that differences in production systems can make a larger difference than the carbon emissions associated with transport alone. In addition, developing countries that rely on the export of particular products as their main source of income could be severely affected by reduced demand for those products resulting from a consumer aversion to food miles (see, for example, the provocatively entitled essay Food Miles or Poverty Eradication? The moral duty to eat African strawberries at Christmas by Müller, 2007). Most people would agree that countries and sectors that are most vulnerable to climate change should be protected from (or at least assisted in managing) unintended negative flow-on effects of changes in lifestyle choices. However, the wider question whether and how countries whose economies are built on the export of carbon-intensive products, particularly the export of crude oil, should be assisted or even compensated for the inevitable income losses they would experience from reduced demand for such products is challenging and causes major debates within the UNFCCC. We return to this issue in chapter 10.