9 Identifying the Costs of Mitigation

Key Messages

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

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

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

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

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

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

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

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

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

9.1 Introduction

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

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

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

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

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

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

9.2 Calculating the costs of cutting GHG emissions

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

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

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

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

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

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

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

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

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[1] A full comparison of the cost estimates used in the Review is given in Annex 9A on www.sternreview.org.uk.
[2] See Drèze and Stern (1987 and 1990), Ahmad and Stern (1991) and Atkinson and Stern (1974).
[3] Expressed informally, shadow prices are opportunity costs: they can often be determined by 'correcting' market prices for market imperfections. For a formal definition, see Drèze and Stern (1987 and 1990). In the models used there, the extra resources for emissions reductions represent a tightening of the general equilibrium constraint and the shadow prices times the quantities involved represent a summary of the overall general equilibrium repercussions.
[4] Similar issues to those arising for marginal changes arise in assessing instruments for reducing GHG emission although in the non-marginal changes, the distributions of costs and benefits can be of special importance.
[5] Of course, if the objective is to calculate the costs of climate-change mitigation to energy users rather than to the world as a whole, the rents can be included.

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

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

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

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

9.3 The range of abatement opportunities

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

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

- To reduce non-fossil fuel emissions, particularly land use, agriculture and fugitive emissions
- To reduce demand for emission-intensive goods and services
- To improve energy efficiency, by getting the same outputs from fewer inputs

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

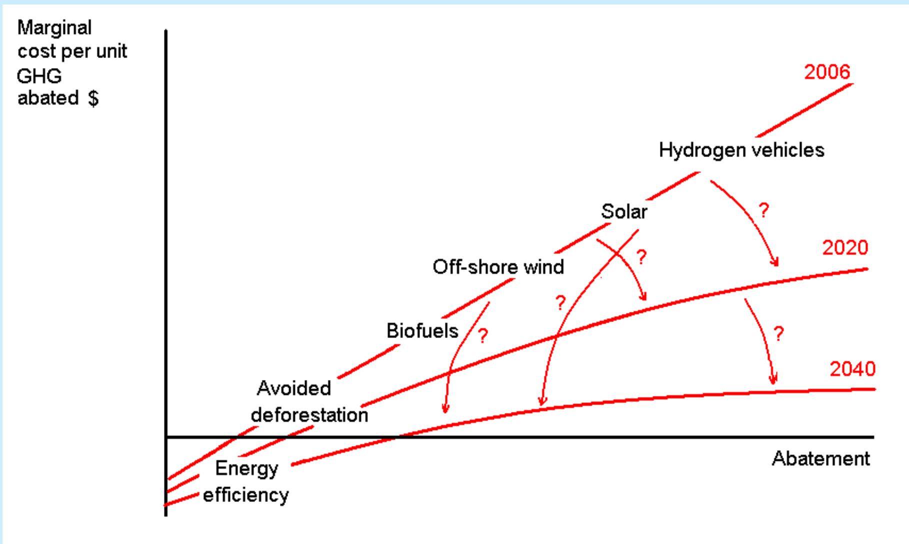
- To switch to technologies which produce fewer emissions and lower the carbon intensity of production

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

The array of abatement opportunities can be assessed in terms of their cost per unit of GHG reduction ($/t$CO_2$e), both at present and through time. In theory, abatement opportunities can be ranked along a continuum of the kind shown in Figure 9.1. This shows that some measures (such as improving energy efficiency and reducing deforestation) can be very cheap, and may even save money. Other measures, such as introducing hydrogen vehicles, may be a very expensive way to achieve emission reductions in the near term, until experience brings costs down.

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

Figure 9.1 Illustrative marginal abatement option cost curve



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

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

[7] See www.sternreview.org.uk

9.4 Cutting non-fossil-fuel related emissions

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

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

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

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

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

[8] Benitez et al. (2005), using a land-cover database, together with econometric modelling and Sathaye et al. (2005).
[9] IPCC (2000) Chapter 3.
[10] Conservation tillage describes tillage methods that leave sufficient crop residue in place to reduce exposure of soil carbon to microbial activity and hence, conserve soil carbon stocks (IPCC (2001)).
[11] IPCC (2001). Revised estimates are expected from the Fourth Assessment Report of IPCC.
[12] Smith et al (2006, forthcoming).

Box 9.1 The costs of reducing emissions by avoiding further deforestation

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

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

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

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

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

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

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

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

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

[13] These figures are calculated from income over 30 years, using a discount rate of 10%, except for Indonesia, which uses 20%.
[14] See Grieg-Gran report prepared for the Stern Review (2006)
[15] Cameroon, Democratic Republic of Congo, Ghana, Bolivia, Brazil, Papua New Guinea, Indonesia, Malaysia.
[16] See for example Sohngen et al (2006)
[17] IPCC (2001). Note this excludes savings from use of biomass and indirect emission reductions from fossil fuels via

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

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

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

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

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

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energy-efficiency measures.

[18] Smith et al (2006 forthcoming).

[19] EPA (forthcoming).

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

[21] EPA (forthcoming).

[22] IPCC (2001)

[23] IPCC (2001)

[24] Stern Review estimate.

Table 9.1 Non-fossil-fuel emissions and savings by sector

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

9.5 Reducing the demand for carbon-intensive goods and services

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

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

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

9.6 Improving energy efficiency

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

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

The technical potential for efficiency improvements to reduce emissions and costs is substantial. Over the past century, efficiency in energy supply improved ten-fold or more in

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

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

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

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

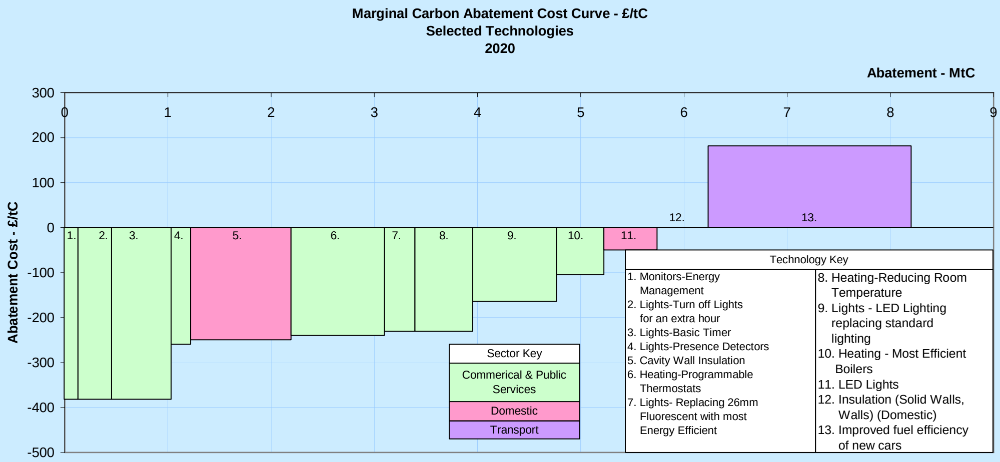
However, the rate of uptake of efficiency measures is often slow, largely because of the existence of market barriers and failures. These include hidden and transaction costs such as the cost of the time needed to plan new investments; a lack of information about the available options; capital constraints;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

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

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

[26] See Hannah (1979)
[27] Assuming 40% thermal efficiency and a c.v. of coal of 8,000kWh/tonne. Pounds (lbs) are a unit of weight: 1 lbs = 0.454 kg.

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



Source: See notes

9.7 Low-carbon technologies

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

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

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

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

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

Box 9.2 Carbon capture and storage (CCS)

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

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

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

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

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

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

[29] Read (2006) discusses how if CCS technologies were to capture emissions from the use of biofuels this could create negative emissions, that is, sequestering carbon dioxide from the atmosphere.
[30] IEA (2006) - ACT MAP is a scenario that includes CCS and where emissions are constrained to near-current levels in 2050 following a technology 'push' for low-carbon technologies.
[31] IPCC (2005)
[32] Page 93 IEA (2005)

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

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

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

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

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

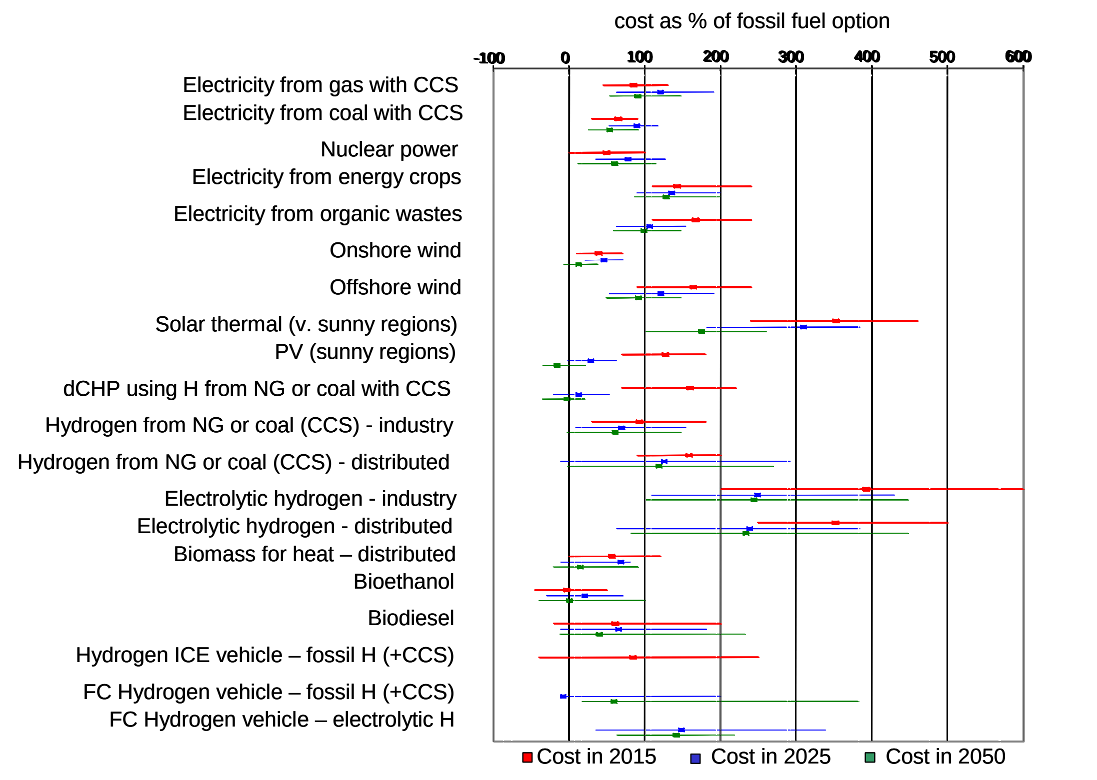
Estimates of the costs per unit of energy of substituting low-carbon-emitting energy sources for fossil fuels over the next 10-20 years are presented in Box 9.3; the technologies shown cover electricity supply, the gas markets (mainly for heat) and transport. The costs are expressed as a central estimate,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

[33] At present sub-sea storage of CO_2 without enhanced oil recovery would be illegal.
[34] Sources include MIT, SPRU, UK CCS, IPCC, UK Energy Review, Sachs and Lackner.
[35] Some compare CCGT, IGCC and supercritical/basic pulverised coal with and without CCS while others compare IGCC with CCS to pulverised coal without or an alternative fossil-fuel mix.
[36] At a cost of $0.9 trillion around $23 per tonne.
[37] Sachs and Lackner, 2005
[38] $280 to $840 billion at $19 - $49/$tCO_2$.
[39] Page 61 IEA, 2006

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

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

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



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

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

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

estimates of global costs should be based on the extraction costs of fossil fuels, not their market prices, which include a significant but uncertain proportion of rents (see Section 9.2).

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

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

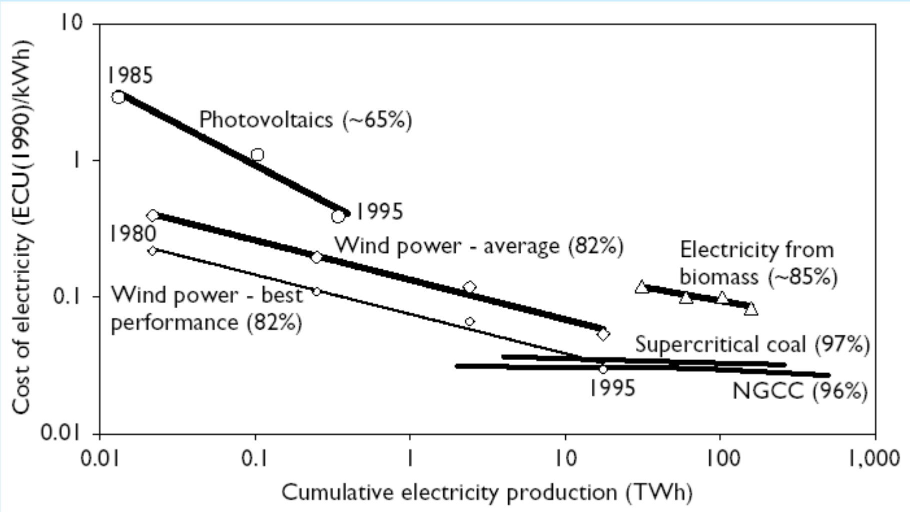
Box 9.4 shows cost trends for selected low-carbon technologies. Economists have fitted 'learning curves' to such data to estimate how much costs might decline with investment and operating experience, as measured by cumulative investment. 'Learning' is of course an important contributor to cost reductions,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

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

Box 9.4 Evidence on learning rates in energy technologies

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

Cost evolution and learning rates for selected technologies



Source: IEA (2000) pp21

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

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

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

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

[42] Note different time periods for different technologies.

Costs, constraints and energy systems in the longer term

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

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

Box 9.5 Biomass: emission saving potential and costs

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

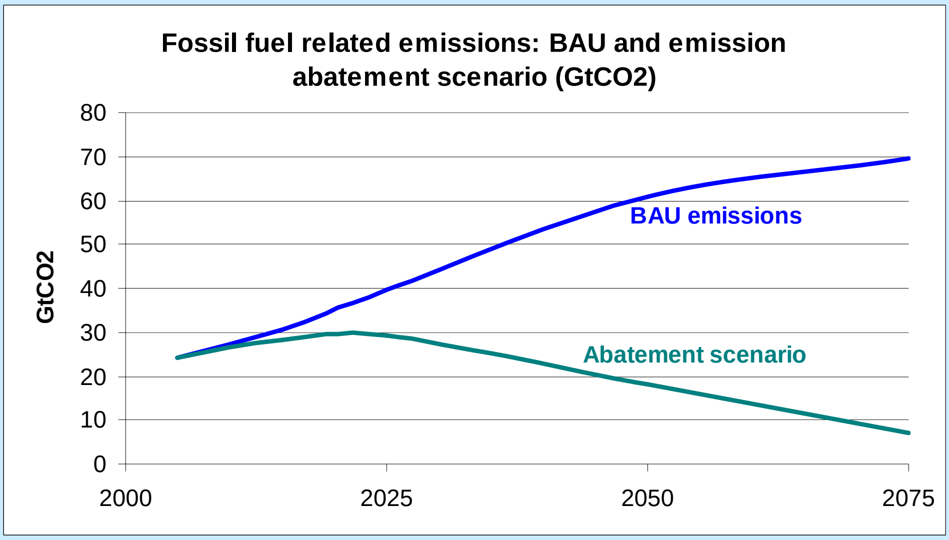
[44] Examples might be polymer-based PVs, with prospects for ‘reel-to-reel’ or batch processing; the generation of hydrogen directly from the action of sunlight on water in the presence of a catalyst (photo-electrolysis); novel methods and materials for hydrogen storage; small and large-scale energy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

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

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

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

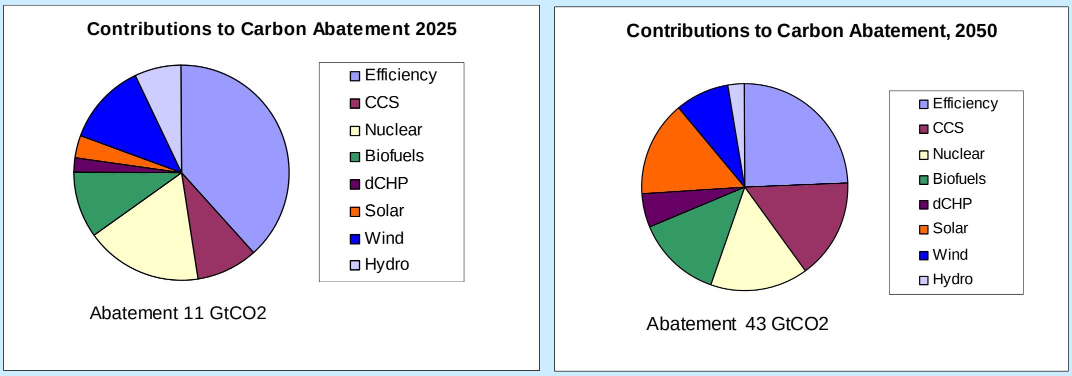
Figure 9.3 Emissions scenarios



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

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

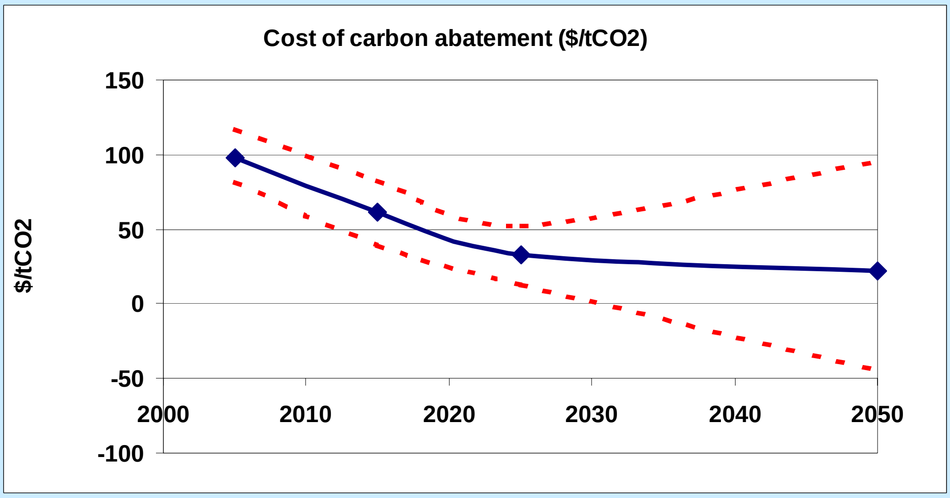
Figure 9.4 The distribution of emission savings by technology



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

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

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



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

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

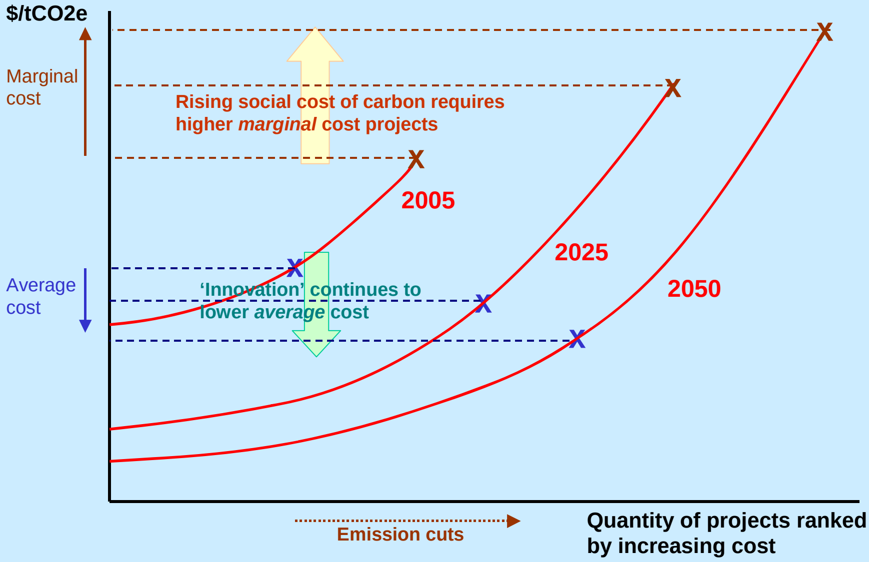
Box 9.6 The relationship between marginal and average costs over time

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

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

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

Illustrative cost per unit of GHG abated for a specific technology



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

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

Table 9.2 Annual total costs of reducing fossil fuel emissions to 18 $GtCO_2$ in 2050			
	2015	2025	2050
Average cost of abatement, $/t CO_2	61	33	22
Emissions Abated $GtCO_2$ (relative to emissions in BAU)	2.2	10.7	42.6
Total cost of abatement, $ billion per year:	134	349	930

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

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

Table 9.3 Sensitivity analysis of global costs of cutting fossil fuel emissions to 18 $GtCO_2$ in 2050 (costs expressed as % of world GDP) [a]			
Case	2015	2025	2050
(i) Central case	0.3	0.7	1.0
(ii) Pessimistic technology case	0.4	0.9	3.3
(iii) Optimistic technology case	0.2	0.2	-1.0
(iv) Low future oil and gas prices	0.4	1.1	2.4
(v) High future oil and gas prices	0.2	0.5	0.2
(vi) High costs of carbon capture and storage	0.3	0.8	1.9
(vii) A lower rate of growth of energy demand	0.3	0.5	0.7
(viii) A higher rate of growth of energy demand	0.3	0.6	1.0
(ix) Including incremental vehicle costs[b]			
• Means	0.4	0.8	1.4
• Ranges	0.3-0.5	0.5-1.1	-0.6- 3.5

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

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

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

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

[49] A full specification of the different cases are set out in the full paper.
[50] Rows (ii) and (iii) provide a rough estimate of the confidence intervals associated with the estimates in row (i).

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

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

9.9 Other technology-based studies on cost

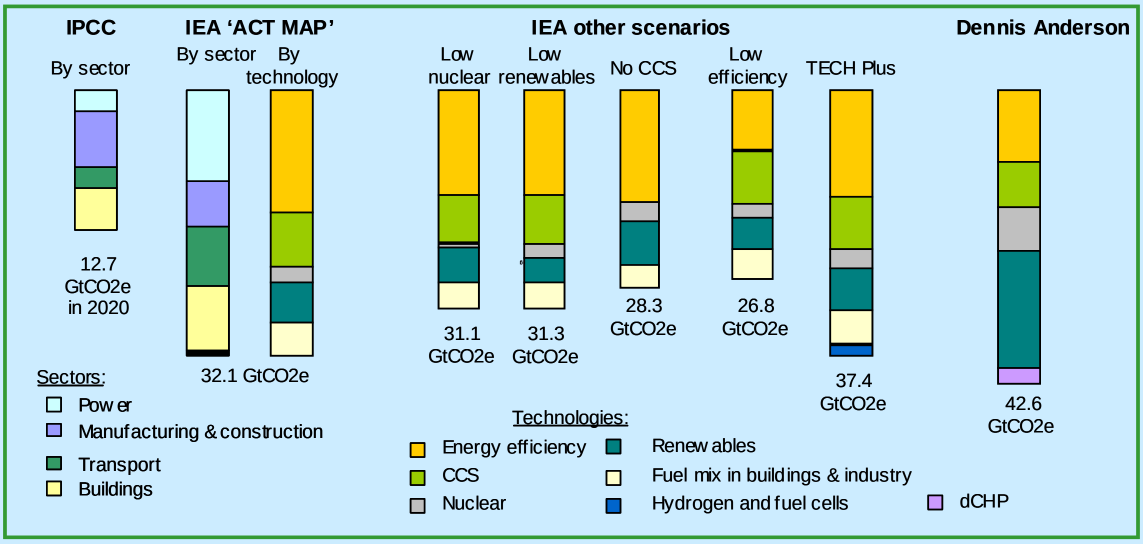
Other modellers have also taken a technology-based approach to looking at emissions reductions and costs. The IEA, in particular, have done detailed work based on their global energy models on the technological and economic feasibility of cutting emissions below business as usual, while also meeting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

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

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

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

Box 9.7 Sources of fossil fuel related emission savings in 2050



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

The IPCC reviewed studies on the extent to which emissions could be cut in the power, manufacturing and construction, transport and buildings sectors. They find that for a cost of less than \$25/tCO_2e, emissions could be cut by 10.8 - 14.7 GtCO_2e in 2020. The savings presented in the diagram are around the mid-point of this range.

The IEA Energy Technology Perspectives report sets out a range of scenarios for reducing energy-related CO_2 emissions by 2050, based on a marginal abatement cost of \$25/tCO_2 in 2050, and investment in research and development of new technologies. The 'ACT MAP' scenario is the central scenario; the others make different assumptions on, for instance, the success of CCS technology and the ability to improve energy efficiency. Total emission savings range from 27 to 37 GtCO_2/year. In all scenarios, the IEA find that the CO_2 intensity of power generation is half current levels by 2050. However there is much less progress in the transport sector in all scenarios apart from TECH PLUS because further abatement from transport is too expensive. To achieve further emission cuts beyond 2050, transport would have to be decarbonised.

The forthcoming World Energy Outlook (2006) depicts an Alternative Policy Scenario that shows how the global energy market could evolve if countries were to adopt all of the policies they are currently considering related to energy security and energy-related CO_2 emissions. This Alternative Policy Scenario cuts fossil fuel emissions by more than 6 GtCO_2/year against the Reference Scenario by 2030, and finds that there is little difference in the investment requirements[51]. The World Energy Outlook (2006) also looks at a more radical path that would bring energy-related CO_2 emissions back to current levels by 2030, through more aggressive action on energy efficiency and transport and energy technologies, including the use of second generation biofuels and carbon capture and storage.

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

9.10 Conclusion

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

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

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

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