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Mitigation from a cross-sectoral perspective

Coordinating Lead Authors:
Terry Barker (UK) and Igor Bashmakov (Russia)

Lead Authors:
Awwad Alharthi (Saudi Arabia), Markus Amann (Austria), Luis Cifuentes (Chile), John Drexhage (Canada), Maosheng Duan (China), Ottmar Edenhofer (Germany), Brian Flannery (USA), Michael Grubb (UK), Monique Hoogwijk (Netherlands), Francis I. Ibitoye (Nigeria), Catrinus J. Jepma (Netherlands), William A. Pizer (USA), Kenji Yamaji (Japan)

Contributing Authors:
Shimon Awerbuch † (USA), Lenny Bernstein (USA), Andre Faaij (Netherlands), Hitoshi Hayami (Japan), Tom Heggedal (Norway), Snorre Kverndokk (Norway), John Latham (UK), Axel Michaelowa (Germany), David Popp (USA), Peter Read (New Zealand), Stefan P. Schleicher (Austria), Mike Smith (UK), Ferenc Toth (Hungary)

Review Editors:
David Hawkins (USA), Aviel Verbruggen (Belgium)

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EXECUTIVE SUMMARY

Mitigation potentials and costs from sectoral studies

The economic potentials for GHG mitigation at different costs have been reviewed for 2030 on the basis of bottom-up studies. The review confirms the Third Assessment Report (TAR) finding that there are substantial opportunities for mitigation levels of about 6 $GtCO_2$-eq involving net benefits (costs less than 0), with a large share being located in the buildings sector. Additional potentials are 7 $GtCO_2$-eq at a unit cost (carbon price) of less than 20 US$/$tCO_2$-eq, with the total, low-cost, potential being in the range of 9 to 18 $GtCO_2$-eq. The total range is estimated to be 13 to 26 $GtCO_2$-eq, at a cost of less than 50 US$/$tCO_2$-eq and 16 to 31 $GtCO_2$-eq at a cost of less than 100 US$/$tCO_2$-eq (370 US$/tC-eq). As reported in Chapter 3, these ranges are comparable with those suggested by the top-down models for these carbon prices by 2030, although there are differences in sectoral attribution *(medium agreement, medium evidence)*.

No one sector or technology can address the entire mitigation challenge. This suggests that a diversified portfolio is required based on a variety of criteria. All the main sectors contribute to the total. In the lower-cost range, and measured according to end-use attribution,[1] the potentials for electricity savings are largest in buildings and agriculture. When attribution is based on point of emission,[2] energy supply makes the largest contribution *(high agreement, much evidence)*.

These estimated ranges reflect some key sensitivities to baseline fossil fuel prices (most studies use relatively low fossil fuel prices) and discount rates. The estimates are derived from the underlying literature, in which the assumptions adopted are not usually entirely comparable and where the coverage of countries, sectors and gases is limited.

Bioenergy

These estimates assume that bioenergy options will be important for many sectors by 2030, with substantial growth potential beyond, although no complete integrated studies are available for supply-demand balances. The usefulness of these options depends on the development of biomass capacity (energy crops) in balance with investments in agricultural practices, logistic capacity, and markets, together with the commercialization of second-generation biofuel production. Sustainable biomass production and use imply the resolution of issues relating to competition for land and food, water resources, biodiversity and socio-economic impact.

Unconventional options

The aim of geo-engineering options is to remove CO_2 directly from the air, for example through ocean fertilization, or to block sunlight. However, little is known about effectiveness, costs or potential side-effects of the options. Blocking sunlight does not affect the expected escalation in atmospheric CO_2 levels, but could reduce or eliminate the associated warming. Disconnecting CO_2 concentration and global temperature in this way could induce other effects, such as the further acidification of the oceans *(medium agreement, limited evidence)*.

Carbon prices and macro-economic costs of mitigation to 2030

Diverse evidence indicates that carbon prices in the range 20–50 US$/$tCO_2$ (US$75–185/tC), reached globally by 2020–2030 and sustained or increased thereafter, would deliver deep emission reductions by mid-century consistent with stabilization at around 550ppm CO_2-eq (Category III levels, see Table 3.10) if implemented in a stable and predictable fashion. Such prices would deliver these emission savings by creating incentives large enough to switch ongoing investment in the world's electricity systems to low-carbon options, to promote additional energy efficiency, and to halt deforestation and reward afforestation.[3] For purposes of comparison, it can be pointed out that prices in the EU ETS in 2005–2006 varied between 6 and 40 US$/$tCO_2$. The emission reductions will be greater (or the price levels required for a given trajectory lower in the range indicated) to the extent that carbon prices are accompanied by expanding investment in technology RD&D and targeted market-building incentives *(high agreement, much evidence)*.

Pathways towards 650ppm CO_2-eq (Category IV levels; see Table 3.10) could be compatible with such price levels being deferred until after 2030. Studies by the International Energy Agency suggest that a mid-range pathway between Categories III and IV, which returns emissions to present levels by 2050, would require global carbon prices to rise to 25 US$/$tCO_2$ by 2030 and be maintained at this level along with substantial investment in low-carbon energy technologies and supply *(high agreement, much evidence)*.

Effects of the measures on GDP or GNP by 2030 vary accordingly (and depend on many other assumptions). For the 650ppm CO_2-eq pathways requiring reductions of 20% global CO_2 or less below baseline, those modelling studies that allow for induced technological change involve lower costs than the full range of studies reported in Chapter 3, depending on policy mix and incentives for the innovation and deployment of low-carbon technologies. Costs for more stringent targets of 550 ppm CO_2-eq requiring 40% CO_2 abatement or less show an

1 In Chapters 4 to 10, the emissions avoided as a result of the electricity saved in various mitigation options are attributed to the end-use sectors using average carbon content for power generation.
2 In 'point-of-emission' attribution, as adopted in Chapter 4, all emissions from power generation are attributed to the energy sector.
3 The forestry chapter also notes that a continuous rise in carbon prices poses a problem: forest sequestration might be deferred to increase profits given higher prices in the future. Seen from this perspective, a more rapid carbon price rise followed by a period of stable carbon prices could encourage more sequestration.

even more pronounced reduction in costs compared to the full range (*high agreement, much evidence*).

Mitigation costs depend critically on the baseline, the modelling approaches and the policy assumptions. Costs are lower with low-emission baselines and when the models allow technological change to accelerate as carbon prices rise. Costs are reduced with the implementation of Kyoto flexibility mechanisms over countries, gases and time. If revenues are raised from carbon taxes or emission schemes, costs are lowered if the revenues provide the opportunity to reform the tax system, or are used to encourage low-carbon technologies and remove barriers to mitigation *(high agreement, much evidence)*.

Innovation and costs

All studies make it clear that innovation is needed to deliver currently non-commercial technologies in the long term in order to stabilize greenhouse gas concentrations *(high agreement, much evidence)*.

A major development since the TAR has been the inclusion in many top-down models of endogenous technological change. Using different approaches, modelling studies suggest that allowing for endogenous technological change reduces carbon prices as well as GDP costs, this in comparison with those studies that largely assumed that technological change was independent of mitigation policies and action. These reductions are substantial in some studies *(medium agreement, limited evidence)*.

Attempts to balance emission reductions equally across sectors (without trading) are likely to be more costly than an approach primarily guided by cost efficiency. Another general finding is that costs will be reduced if policies that correct the two relevant market failures are combined by incorporating the damage resulting from climate change in carbon prices, and the benefits of technological innovation in support for low-carbon innovation. An example is the recycling of revenues from tradeable permit auctions to support energy efficiency and low-carbon innovations. Low-carbon technologies can also diversify technology portfolios, thereby reducing risk *(high agreement, much evidence)*.

Incentives and investment

The literature emphasizes the need for a range of cross-sectoral measures in addition to carbon pricing, notably in relation to regulatory and behavioural aspects of energy efficiency, innovation, and infrastructure. Addressing market and regulatory failures surrounding energy efficiency, and providing information and support programmes can increase responsiveness to price instruments and also deliver direct emission savings *(high agreement, much evidence)*.

Innovation may be greatly accelerated by direct measures and one robust conclusion from many reviews is the need for public policy to promote a broad portfolio of research. The literature also emphasizes the need for a range of incentives that are appropriate to different stages of technology development, with multiple and mutually supporting policies that combine technology push and pull in the various stages of the 'innovation chain' from R&D through the various stages of commercialization and market deployment. In addition, the development of cost-effective technologies will be rewarded by well-designed carbon tax or cap and trade schemes through increased profitability and deployment. Even so, in some cases, the short-term market response to climate policies may lock in existing technologies and inhibit the adoption of more fruitful options in the longer term (*high agreement, much evidence*).

Mitigation is not a discrete action: investment, in higher or lower carbon options, is occurring all the time. The estimated investment required is around $20 trillion in the energy sector alone out to 2030. Many energy sector and land use investments cover several decades; buildings, urban and transport infrastructure, and some industrial equipment may influence emission patterns over the century. Emission trajectories and the potential to achieve stabilization levels, particularly in Categories A and B, will be heavily influenced by the nature of these investments. Diverse policies that deter investment in long-lived carbon-intensive infrastructure and reward low-carbon investment could maintain options for these stabilization levels at lower costs *(high agreement, much evidence).*

However, current measures are too uncertain and short-term to deliver much lower-carbon investment. The perceived risks involved mean that the private sector will only commit the required finance if there are incentives (from carbon pricing and other measures) that are clearer, more predictable, longer-term and more robust than provided for by current policies *(high agreement, much evidence).*

Spillover effects from Annex I action

Estimates of carbon leakage rates for action under Kyoto range from 5 to 20% as a result of a loss of price competitiveness, but they remain very uncertain. The potential beneficial effect of technology transfer to developing countries arising from technological development brought about by Annex I action may be substantial for energy-intensive industries. However, it has not yet been quantified reliably. As far as existing mitigation actions, such as the EU ETS, are concerned, the empirical evidence seems to indicate that competitive losses are not significant, confirming a finding in the TAR *(medium agreement, limited evidence)*.

Perhaps one of the most important ways in which spillover from mitigation action in one region affects others is through its effect on world fossil fuel prices. When a region reduces its local fossil fuel demand as a result of mitigation policy, it will reduce world demand for that commodity and so put downward pressure on prices. Depending on the response from fossil-fuel producers, oil, gas or coal prices may fall, leading to loss of revenue for the producers, and lower costs of imports for the consumers. Nearly all modelling studies that have been reviewed indicate more pronounced adverse effects on countries with high shares of oil output in GDP than on most of the Annex I countries taking abatement action *(high agreement, much evidence)*.

Co-benefits of mitigation action

Co-benefits of action in the form of reduced air pollution, more energy security or more rural employment offset mitigation costs. While the studies use different methodological approaches, there is general consensus for all world regions analyzed that near-term health and other benefits from GHG reductions can be substantial, both in industrialized and developing countries. However, the benefits are highly dependent on the policies, technologies and sectors chosen. In developing countries, much of the health benefit could result from improvements in the efficiency of, or switching away from, the traditional use of coal and biomass. Such near-term co-benefits of GHG control provide the opportunity for a true no-regrets GHG reduction policy in which substantial advantages accrue even if the impact of human-induced climate change itself turns out to be less than that indicated by current projections *(high agreement, much evidence)*.

Adaptation and mitigation from a sectoral perspective

Mitigation action for bioenergy and land use for sinks are expected to have the most important implications for adaptation. There is a growing awareness of the unique contribution that synergies between mitigation and adaptation could provide for the rural poor, particularly in the least developed countries: many actions focusing on sustainable policies for managing natural resources could provide both significant adaptation benefits and mitigation benefits, mostly in the form of carbon sink enhancement *(high agreement, limited evidence).*

11.1 Introduction

This chapter takes a cross-sectoral approach to mitigation options and costs, and brings together the information in Chapters 4 to 10 to assess overall mitigation potential. It compares these sectoral estimates with the top-down estimates from Chapter 3, adopting a more short- and medium-term perspective, taking the assessment to 2030. It assesses the cross-sectoral and macro-economic cost literatures since the Third Assessment Report (TAR) (IPCC, 2001), and those covering the transition to a low-carbon economy, spillovers and co-benefits of mitigation.

The chapter starts with an overview of the cross-cutting options for mitigation policy (Section 11.2), including technologies that cut across sectors, such as hydrogen-based systems and options not covered in earlier chapters, examples being ocean fertilization, cloud creation and bio- and geo-engineering. Section 11.3 covers overall mitigation potential by sector, bringing together the various options, presenting the assessment of the sectoral implications of mitigation, and comparing bottom-up with top-down estimates. Section 11.4 covers the literature on the macro-economic costs of mitigation.

Since the TAR, there is much more literature on the quantitative implications of introducing endogenous technological change into the models. Many studies suggest that higher carbon prices and other climate policies will accelerate the adoption of low-carbon technologies and lower macroeconomic costs, with estimates ranging from a negligible amount to negative costs (net benefits). Section 11.5 describes the effects of introducing endogenous technological change into the models, and particularly the effects of inducing technological change through climate policies.

The remainder of the chapter looks at interactions of various kinds: Section 11.6 links the medium-term to the long-term issues discussed in Chapter 3, linking the shorter-term costs and social prices of carbon to the longer-term stabilization targets; 11.7 covers spillovers from action in one group of countries on the rest of the world; 11.8 covers co-benefits (particularly local air quality benefits) and costs; and 11.9 deals with synergies and trade-offs between mitigation and adaptation.

11.2 Technological options for cross-sectoral mitigation: description and characterization

This section covers technologies that affect many sectors (11.2.1) and other technologies that cannot be attributed to any of the sectors covered in Chapters 4 to 10 (geo-engineering options etc. in 11.2.2). The detailed consolidation and synthesis of the mitigation potentials and costs provided in Chapters 4 to 10 are covered in the next section, 11.3.

11.2.1 Cross-sectoral technological options

Cross-sectoral mitigation technologies can be broken down into three categories in which the implementation of the technology:

1. occurs in parallel in more than one sector;
2. could involve interaction between sectors, or
3. could create competition among sectors for scarce resources.

Some of the technologies implemented in parallel have been discussed earlier in this report. Efficient electric motor-driven systems are used in the industrial sector (Section 7.3.2) and are also a part of many of the technologies for the buildings sector, e.g. efficient heating, ventilation and air conditioning systems (Section 6.4.5). Solar PV can be used in the energy sector for centralized electricity generation (Section 4.3.3.6) and in the buildings sector for distributed electricity generation (Section

6.4.7). Any improvement in these technologies in one sector will benefit the other sectors.

On a broad scale, information technology (IT) is implemented in parallel across sectors as a component of many end-use technologies, but the cumulative impact of its use has not been analyzed. For example, IT is the basis for integrating the control of various building systems, and has the potential to reduce building energy consumption (Section 6.4.6). IT is also the key to the performance of hybrids and other advanced vehicle technologies (Section 5.3.1.2). Smart end-use devices (household appliances, etc) could use IT to program their operation at times when electricity demand is low. This could reduce peak demand for electricity, resulting in a shift to base load generation, which is usually more efficient (Hirst, 2006). The impact of such a switch on CO_2 emissions is unknown, because it is easy to construct cases where shifts from peak load to base load would increase CO_2 emissions (e.g., natural-gas-fired peak load, but coal-fired base load). General improvements in IT, e.g. cheaper computer chips, will benefit all sectors, but applications have to be tailored to the specific end-use. Of course, the net impact of IT on greenhouse gas emissions could result either in net reductions or gains, depending for example on whether or not efficiency gains are offset by increases in production.

An example of a group of technologies that could involve interaction between sectors is gasification/hydrogen/carbon dioxide capture and storage (CCS) technology (IPCC, 2005 and Chapter 4.3.6). While these technologies can be discussed separately, they are interrelated and being applied as a group enhances their CO_2-emission mitigation potential. For example, CCS can be applied as a post-combustion technology, in which case it will increase the amount of resource needed to generate a unit of heat or electricity. Using a pre-combustion approach, i.e. gasifying fossil fuels to produce hydrogen that can be used in fuel cells or directly in combustion engines, may improve overall energy efficiency. However, unless CCS is used to mitigate the CO_2 by-product from this process, the use of that hydrogen will offer only modest benefits. (See Section 5.3.1.4 for a comparison of fuel cell and hybrid vehicles.) Adding CCS would make hydrogen an energy carrier, providing a low CO_2 emission approach for transportation, buildings, or industrial applications. Implementation of fuel cells in stationary applications could provide valuable learning for vehicle application; in addition, fuel cell vehicles could provide electric power to homes and buildings (Romeri, 2004).

In the longer term, hydrogen could be manufactured by gasifying biomass – an approach which has the potential to achieve negative CO_2 emissions (IPCC, 2005) – or through electrolysis using carbon-free sources of electricity, a zero CO_2 option. In the even longer term, it may be possible to produce hydrogen by other processes, e.g. biologically, using genetically-modified organisms (GCEP, 2005). However, none of these longer-term technologies are likely to have a significant impact before 2030, the time frame for this analysis.

Biomass is an example of a cross-sectoral technology which may compete for resources. Any assessment of the use of biomass, e.g., as a source of transportation fuels, must consider competing demands from other sectors for the creation and utilization of biomass resources. Technical breakthroughs could allow biomass to make a larger future contribution to world energy needs. Such breakthroughs could also stimulate the investments required to improve biomass productivity for fuel, food and fibre. See Chapter 4 and Section 11.3.

Another example of resource competition involves natural gas. Natural gas availability could limit the application of some short- to medium-term mitigation technology. Switching to lower carbon fuels, e.g. from coal to natural gas for electricity generation, or from gasoline or diesel to natural gas for vehicles, is a commonly cited short-term option. Because of its higher hydrogen content, natural gas is also the preferred fossil fuel for hydrogen manufacture. Discussion of these options in one sector rarely takes natural gas demand from other sectors into account.

In conclusion, there are several important interactions between technologies across sectors that are seldom taken into account. This is an area of energy system modelling that requires further investigation.

11.2.2 Ocean fertilization and other geo-engineering options

Since the TAR, a body of literature has developed on alternative, geo-engineering techniques for mitigating climate change. This section focuses on apparently promising techniques: ocean fertilization, geo-engineering methods for capturing and safely sequestering CO_2 and reducing the amount of sunlight absorbed by the earth's atmospheric system. These options tend to be speculative and many of their environmental side-effects have yet to be assessed; detailed cost estimates have not been published; and they are without a clear institutional framework for implementation. Conventional carbon capture and storage is covered in Chapter 4, Section 4.3.6 and the IPCC Special Report (2005) on the topic.

11.2.2.1 Iron and nitrogen fertilization of the oceans

Iron fertilization of the oceans may be a strategy for removing CO_2 from the atmosphere. The idea is that it stimulates the growth of phytoplankton and therefore sequesters CO_2 in the form of particulate organic carbon (POC). There have been eleven field studies in different ocean regions with the primary aim of examining the impact of iron as a limiting nutrient for phytoplankton by the addition of small quantities (1–10 tonnes) of iron sulphate to the surface ocean. In addition, commercial tests are being pursued with the combined (and conflicting) aims of increasing ocean carbon sequestration and productivity. It should be noted, however, that iron addition will only stimulate phytoplankton growth in ~30% of the oceans (the Southern

Ocean, the equatorial Pacific and the Sub-Arctic Pacific), where iron depletion prevails. Only two experiments to date (Buesseler and Boyd, 2003) have reported on the second phase, the sinking and vertical transport of the increased phytoplankton biomass to depths below the main thermocline (>120m). The efficiency of sequestration of the phytoplankton carbon is low (<10%), with the biomass being largely recycled back to CO_2 in the upper water column (Boyd *et al.*, 2004). This suggests that the field-study estimates of the actual carbon sequestered per unit iron (and per dollar) are over-estimates. The cost of large-scale and long-term fertilization will also be offset by CO_2 release/emission during the acquisition, transportation and release of large volumes of iron in remote oceanic regions. Potential negative effects of iron fertilization include the increased production of methane and nitrous oxide, deoxygenation of intermediate waters and changes in phytoplankton community composition that may cause toxic blooms and/or promote changes further along the food chain. None of these effects have been directly identified in experiments to date, partly due to the time and space constraints.

Nitrogen fertilization is another option (Jones, 2004) with similar problems and consequences.

11.2.2.2 Technologically-varied solar radiative forcing

The basic principle of these technologies is to reduce the amount of sunlight accepted by the earth's system by an amount sufficient to compensate for the heating resulting from enhanced atmospheric CO_2 concentrations. For CO_2 levels projected for 2100, this corresponds to a reduction of about 2%. Three techniques are considered:

A. Deflector System at Earth-Sun L-1[4] point. The principle underlying this idea (e.g. Seifritz (1989), Teller *et al. (2004)*, Angel (2006)) is to install a barrier to sunlight measuring about 106 km^2 at or close to the L-1 point. Teller *et al.* estimate that its mass would be about 3000 t, consisting of a 30µm metallic screen with 25nm ribs.[5] They envisage it being spun in situ, and emplaced by one shuttle flight a year over 100 years. It should have essentially zero maintenance. The cost has not yet been determined. Computations by Govindasamy *et al. (2003)* suggest that this scheme could markedly reduce regional and seasonal climate change.

B. Stratospheric Reflecting Aerosols. This technique involves the controlled scattering of incoming sunlight with airborne sub-microscopic particles that would have a stratospheric residence time of about 5 years. Teller *et al.* (2004) suggest that the particles could be: (a) dielectrics; (b) metals; (c) resonant scatterers. Crutzen (2006) proposes (d) sulphur particles. The implications of these schemes, particularly with regard to stratospheric chemistry, feasibility and costs, require further assessment (Cicerone, 2006).

C. Albedo Enhancement of Atmospheric Clouds. This scheme (Latham, 1990; 2002) involves seeding low-level marine stratocumulus clouds – which cover about a quarter of the Earth's surface – with micrometre-sized aerosol, formed by atomizing seawater. The resulting increases in droplet number concentrations in the clouds raises cloud albedo for incoming sunlight, resulting in cooling which could be controlled (Bower *et al.*, 2006) and be sufficient to compensate for global warming. The required seawater atomization rate is about 10 m3/sec. The costs would be substantially less than for the techniques mentioned under B. An advantage is that the only raw material required is seawater but, while the physics of this process are reasonably well understood, the meteorological ramifications need further study.

These schemes do not affect the expected escalation in atmospheric CO_2 levels, but could reduce or eliminate the associated warming. Disconnecting CO_2 concentration and global temperature in this way could have beneficial consequences such as increases in the productivity of agriculture and forestry. However, there are also risks and this approach will not mitigate or address other effects such as increasing ocean acidification (see IPCC, 2007b, Section 4.4.9).

11.3 Overall mitigation potential and costs, including portfolio analysis and cross-sectoral modelling

This section synthesizes and aggregates the estimates from chapters 4 to 10 and reviews the literature investigating cross-sectoral effects. The aim is to identify current knowledge about the integrated mitigation potential and/or costs covering more than two sectors. There are many specific policies for reducing GHG emissions (see Chapter 13). Non-climate policies may also yield substantial GHG reductions as co-benefits (see Section 11.8 and Chapter 12). All these policies have direct sectoral effects. They also have indirect cross-sectoral effects, which are covered in this section and which diffuse across countries. For example, domestic policies promoting a new technology to reduce the energy use of domestic lighting lead to reductions in emissions of GHG from electricity generation. They may also result in more exports of the new technology and, potentially, additional energy savings in other countries. This section also looks at studies relating to a portfolio analysis of mitigation options.

4 This is the L-1 Lagrange point between the sun and the earth.
5 µm stands for micrometre and Nm stands for nanometre (see glossary).

11.3.1 Integrated summary of sectoral emission potentials

Chapters 4 to 10 assessed the economic potential of GHG mitigation at a sectoral scale for the time frame out to 2030 (for a discussion of the different definitions of potential, see Chapter 2). These bottom-up estimates are derived using a variety of literature sources and various methodologies, as discussed in the underlying chapters. This section derives ranges of aggregate economic potentials for GHG mitigation over different costs (i.e. carbon prices) at year-2000 prices.

11.3.1.1 Problems in aggregating emissions

In compiling estimates of this kind, various issues must be considered:

Comparability: There is no common, standardized approach in the underlying literature that is used systematically for assessing the mitigation potential. The comparability of data is therefore far from perfect. The comparability problem was addressed by using a common format to bring together the variety of data found in the literature (as shown below in section 11.3.1.3 and Table 11.3), acknowledging that any aberrations due to a lack of a common methodological base may in part cancel each other out in the aggregation process. Some extrapolations were necessary, for example in the residential sector where the literature mostly refers to 2020. The final result can be considered the best result that is possible and it is accurate within the uncertainty ranges provided.

Coverage: Chapters 4 to 10 together cover virtually all sources of greenhouse gas emissions. However, for parts of some sectors, it was not possible to derive emission reduction potentials from the literature. Furthermore, no quantified emission reduction potentials were available for some options. This leads to a certain under-estimation of the emission reduction potential as discussed in Section 11.3.1.3. The under-estimation of the total mitigation potential is limited, but not negligible.

Baselines: Ideally, emission reduction potentials should adopt a common baseline. Some emission scenarios, such as those developed for the Special Report on Emission Scenarios (IPCC, 2000), are suitable for worldwide, sectoral and multi-gas coverage. However, for a number of sectors, such baselines are not detailed enough to serve as a basis for making bottom-up emission reduction calculations. The baselines used are described and discussed further in Section 11.3.1.2.

Aggregation: The aggregation of mitigation potentials for various sectors is complicated by the fact that mitigation action in one sector may affect mitigation potential in another. There is a risk of double counting of potentials. The problem and the procedures used to overcome this risk are explained in Section 11.3.1.3. In addition the baselines differ to some extent.

11.3.1.2 The baseline

All mitigation potentials have to be estimated against a baseline. The main baseline scenarios used for compiling the assessments in the chapters are the SRES B2 and A1B marker scenarios (IPCC, 2000) and the World Energy Outlook 2004 (WEO2004) (IEA, 2004). The assumed emissions in the three baseline scenarios vary in magnitude and regional distribution. The baseline scenarios B2 and WEO2004 are comparable in the main assumptions for population, GDP and energy use. Figure 11.1 shows that the emissions are also comparable. Scenario A1B, which assumes relatively higher economic growth, shows substantially higher emissions in countries outside the OECD/EIT region.

The crude oil prices assumed in SRES B2 and WEO2004 are of the same order of magnitude. The oil prices in the SRES scenarios vary across studies. For the MESSAGE model (B2 scenario), the price is about 25 US$/barrel (Riahi *et al.*, 2006). In the case of the WEO2004, for example, the oil price assumed in 2030 is 29 US$/barrel. These prices (and all other energy price assumptions) are substantially lower than those prevailing in 2006 and assumed for later projections (IEA, 2005 and 2006b). The 2002–6 rises in world energy prices are also reflected in the energy futures markets for at least another five to ten years. In fact, the rise in crude oil prices during this period, some 50 US$/barrel, is comparable to the impact of a 100 US$/t$CO_2$-eq increase in the price of carbon. However, it is still uncertain whether these price increases will have a significant impact on the long-term energy price trend.

Higher energy prices and further action on mitigation may reinforce each other in their impact on mitigation potential, although it is still uncertain how and to what extent. On the one hand, for instance, economies of scale may facilitate the introduction of some new technologies if supported by a higher

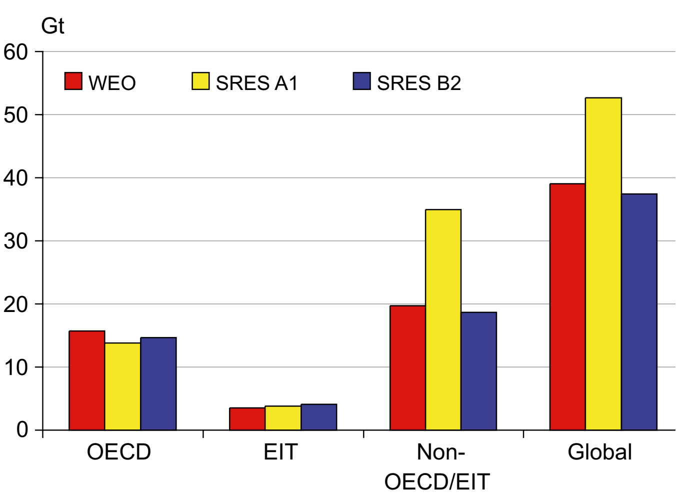

Figure 11.1: *Energy-related CO_2-only emissions per world region for the year 2030 in the World Energy Outlook, and in the SRES B2 and A1B scenarios*

Source: Price et al., 2006.

Table 11.1: *Overview of the global emissions for the year 2004 and the baseline emissions for all GHGs adopted for the year 2030 (in $GtCO_2$-eq)*

	Global emissions 2004 (allocated to the end-use sector)[a, c]	Global emissions 2004 (point of emissions)[a, b]	Type of baseline used[d]	Global emissions 2030 (allocated to the end-use sector)	Global emissions 2030 (point of emissions)
Energy supply	-[j]	12.7	WEO	-[j, f)]	15.8[f)]
Transport	6.4	6.4	WEO	10.6[f)]	10.6[f)]
Buildings	9.2	3.9	Own	14.3[f)]	5.9[e) f)]
Industry	12.0	9.5	B2/USEPA	14.6	8.5[g)]
Agriculture	6.6	6.6	B2/FAO	8.3	8.3
LULUCF/Forestry[k)]	5.8	5.8	Own	5.8[h)]	5.8[h)]
Waste[i)]	1.4	1.4	A1B	2.1	2.1

Notes:

a) The emissions in the year 2004 as reported in the sectoral chapters and Chapter 1, Figure 1.3a/b.

b) The allocation to point of emission means that the emissions are allocated to the sector where the emission takes place. For example, electricity emissions are allocated to the power sector. There is a difference between the sum when allocating the emissions in different ways. This is explained by the exclusion of electricity emissions from the agricultural and transport sectors due to lack of data and by the exclusion of emissions from conversion of energy as most end-use emissions are based on final energy supply.

c) 'Allocated to the end-use sector' means that the emissions are allocated to the sectors that use the energy. For example, electricity emissions are allocated to the end-use sectors, mainly buildings and industry. Emissions from extraction and distribution are not included here.

d) See text for further clarification on the type of baselines used.

e) This figure is based on the assumption that the share of electricity-related emissions in the constructed baseline in Chapter 6 is the same as for the SRES B2 scenario. According to Price et al. (2006), the electricity-related emissions amount to 59%. 59% of the baseline (14.3 GtCO2-eq) is 8.4 GtCO2-eq. The remaining emissions are allocated to the buildings sector.

f) 2030 emissions of the F-gases are not available for the Transport, Buildings, and Energy Supply sectors.

g) Source: Price et al., 2006.

h) No baseline emissions for the year 2030 from the forestry sector are reported. See 9.4.3. On the basis of top-down models, it can be expected that the emissions in 2030 will be similar to 2004.

i) The data for waste include waste disposal, wastewater and incineration. The emissions from wastewater treatment are for the years 2005 and 2020.

j) The emissions from conversion losses are not included due to lack of data.

k) Note that the peat fires and other bog fires, as mentioned in Chapter 1, are not included here. Nor are they included in Chapters 8 and 9.

energy price trend. On the other hand, it is also conceivable that, once some cost-effective innovation has already been triggered by higher energy prices, any further mitigation action through policies and measures may become more costly and difficult. Finally, although general energy prices rises will encourage energy efficiency, the mix of the different fuel prices is also important. Oil and gas prices have risen substantially in relation to coal prices 2002–6, and this will encourage greater use of coal, for example in electricity generation, increasing GHG emissions.

As a rule, the SRES B2 and WEO2004 baselines were both used for the synthesis of the emission mitigation potentials by sector. Most chapters have reported the mitigation potential for at least one of these baseline scenarios. There are a few exceptions. Chapter 5 (transportation) uses a different, more suitable, scenario (WBCSD, 2004). However, it is comparable to WEO2004. Chapter 6 (buildings) constructed a baseline scenario with CO_2 emissions between those of the SRES B2 and A1B marker scenarios taken from the literature (see Section 6.5). The agriculture and forestry sectors based their mitigation potential on changes in land use as deduced from various scenarios (including marker scenarios, see Sections 8.4.3 and 9.4.3). The SRES scenarios did not include enough detail for the waste sector, so Chapter 10 used the GDP and population figures from SRES A1B and the methodologies described in IPCC Guidelines 2006 (see Section 10.4.7).

Table 11.1 compares the emissions of the different sectoral baselines for 2004 and 2030 against a background of the end-use and point-of-emission allocation of emissions attributed to electricity use. Since the 2030 data are from studies that differ in terms of coverage and comparability, they should not be directly aggregated across the different sectors and therefore no totals across all sectors are shown in Table 11.1[6]. An important difference between the WEO baseline and SRES B2 is that the WEO emissions do not include all non-CO_2 GHG emissions.

11.3.1.3 Synthesizing the potentials from Chapters 4 to 10 involving electricity

When aggregating the sectoral mitigation potentials, the links between sectors need to be considered (Figure 11.2). For example, the options in electricity supply interact with those for electricity demand in the buildings and industry sectors. On the supply side, fossil-fuel electricity can be substituted by low-CO_2 or CO_2-free technologies such as renewable sources, nuclear energy, bioenergy or fossil fuel in combination with

6 However, since the ranges allow for uncertainties in the baseline, they can be aggregated under specific assumptions and these ranges are shown below.

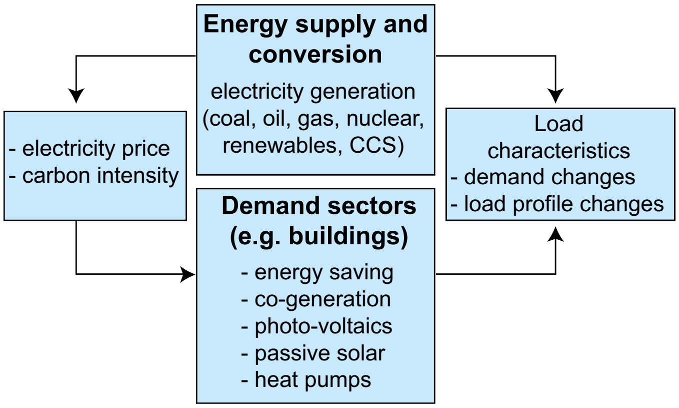

Figure 11.2: *Interaction of CO_2 mitigation measures between electricity supply and demand sectors*

carbon capture and storage. On the demand side, the buildings and the industrial sectors have options for electricity savings. The emission reductions from these two sets of options cannot be aggregated since emission reductions in demand reduce the potential for those in supply and vice-versa.

To overcome this problem, the following approach was adopted: The World Energy Outlook (IEA, 2004) for the year 2030 was used as the baseline. The potentials from electricity savings in the buildings and the industry sectors were estimated first. Electricity savings then reduce demand for electricity. This sequence was followed because electricity savings can be achieved at relatively low cost and their implementation can therefore be expected first. Electricity savings were converted to emission reductions using the average carbon intensity of the electricity supply in the baseline for the year 2030. In reality, it can be expected that electricity savings would result in a relatively larger reduction in fossil-fuel electricity generation than electricity generation involving low marginal costs such as renewables and nuclear. This is because, in the operating system, low-cost generation is normally called on before high-cost generation. However, this response depends on local conditions and it is not appropriate to consider it here. However, it does imply that the emission reductions for electricity savings reported here are an under-estimate. This under-estimate becomes more pronounced with higher carbon prices, and higher marginal costs for fossil fuels.

The detailed sequence is as follows:

1. Electricity savings from the measures in the buildings and industry sector were subtracted from the baseline supply estimates to obtain the corrected electricity supply for 2030.
2. No early withdrawal of plant or stranded assets is assumed. Low-carbon options can therefore only be applied to new electricity supply.
3. The new electricity supply required to 2030 was calculated from 1) additional new capacity between 2010 and 2030 and 2) capacity replaced in the period 2010–2030 after an assumed average plant lifetime of 50 years (see Chapter 4.4.3).
4. The new electricity supply required was divided between available low-carbon supply options. As the cost estimates were lowest for a fuel switch from coal to natural gas supply, it was assumed that this would take place first. In accordance with Chapter 4 it was assumed that 20% of the new coal plants required would be substituted by gas technologies.
5. An assessment was made of the prevented emissions from the other low-carbon substitution options after the fuel switch. The following technologies were taken into account: renewables (wind and geothermal), bioenergy, hydro, nuclear and CCS. It was assumed that the fossil fuel requirement in the baseline (after adjustments for the previous step) was met by these low-carbon intensive technologies. The substitution was made on the basis of relative maximum technical potential. The same breakdown as in Section 4.4.3 was used for the low-carbon options.
6. It was then possible to estimate the resulting mitigation potential for the energy sector, after savings in the end-use sectors buildings and industry.
7. For the buildings and industry sectors, the mitigation potential was broken down into emission savings resulting from less electricity use and the remainder.
8. For sectors other than energy, buildings and industry, the data given in the chapters were used for the overall aggregation.

When evaluating mitigation potential in the energy supply sector, the calculations in Chapter 4 did not subtract the electricity savings from the buildings and industry sectors (see Chapter 4, Table 4.19). Adopting this order (which is not the preferred order, as explained above) implies first taking all the mitigation measures in the energy sector and then applying the electricity savings from buildings and industry sectors. This would result in different mitigation potentials for each of the sectors and mitigation measures, although the total will not change. See Appendix 11.1 for a further discussion of the methodology and details of the calculation.

In the case of the other sectors, the data given in the chapters were used for the overall aggregation. The mitigation potential for the buildings and industry sectors was broken down into emission savings for lower electricity use and the remainder, so that the potential could be re-allocated where necessary to the power sector.

11.3.1.4 Synthesizing the potentials from Chapters 4 to 10 involving biomass

Biomass supplies originate in agriculture (residues and cropping), forestry, waste supplies, and in biomass processing industries (such as the paper & pulp and sugar industries). Key applications for biomass are conversion to heat, power, transportation fuels and biomaterials. Information about biomass supplies and utilization is distributed over the relevant chapters in this report and no complete integrated studies are available for biomass supply-demand balances and biomass potential.

Biomass demand from different sectors

Demand for biomass as transportation fuel involves the production of biofuels from agricultural crops such as sugar cane, rape seed, corn, etc., as well as potentially 'second-generation' biofuels produced from lignocellulosic biomass. The first category dominates in the shorter term. The penetration of second-generation biofuels depends on the speed of technological development and the market penetration of gasification technology for synfuels and hydrolysis technology for the production of ethanol from woody biomass. Demand projections for primary biomass in Chapter 5 are largely based on WEO-IEA (2006) global projections, with a relatively wide range of about 14 to 40 EJ of primary biomass, or 8–25 EJ of fuel. However, there are also higher estimates ranging from 45 to 85 EJ demand for primary biomass in 2030 (or roughly 30–50 EJ of fuel) (see Chapter 5).

Demand for biomass for power and heat is considered in Chapter 4 (energy). Demand for biomass for heat and power will be strongly influenced by the availability and introduction of competing technologies such as CCS, nuclear power, wind energy, solar heating, etc. The projected demand in 2030 for biomass would be around 28–43 EJ according to the data used in Section 4.4.3.3. These estimates focus on electricity generation. Heat is not explicitly modelled or estimated in the WEO, resulting in an under-estimate of total demand for biomass.

Industry is an important user of biomass for energy, most notably the paper & pulp industry and the sugar industry, which both use residues for generating process energy (steam and electricity). Chapter 7 highlights improvements in energy production from such residues, most notably the deployment of efficient gasification/combined cycle technology that could strongly improve efficiencies in, for example, pulp and sugar mills. Mitigation potentials reducing the demand for such commodities or raising the recycling rate for paper will not result in *additional* biomass demand. Biomass can also be used for the production of chemicals and plastics, and as a reducing agent for steel production (charcoal) and for construction purposes (replacing, for example, metals or concrete). Projections for such production routes and subsequent demand for biomass feedstocks are not included in this report, since their deployment is expected to be very limited (see Chapter 7).

In the *built environment***,** biomass is used in particular for heating for both non-commercial uses (and also as cooking fuel) and in modern stoves. The use of biomass for domestic heating could represent a significant mitigation potential. No quantitative estimates are available of future biomass demand for the built environment (for example, heating with pellets or cooking fuels) (Chapter 6).

Biomass supplies

Biomass production on agricultural and degraded lands. Table 11.2 summarizes the biomass supply energy potentials discussed in Chapters 8 (agriculture), 9 (Forestry) and 10 (waste). Those potentials are accompanied by considerable uncertainties. In addition, the estimates are derived from scenarios for the year 2050. The largest contribution could come from energy crops on arable land, assuming that efficiency improvements in agriculture are fast enough to outpace food demand so as to avoid increased pressure on forests and nature areas. Section 8.4.4.2 provides a range from 20–400 EJ. The highest estimate is a technical potential for 2050. Technically, the potentials for such efficiency increases are very large, but the extent to which such potentials can be exploited over time is still poorly studied. Studies assume the successful introduction of biomass production in key regions as Latin America, Sub-Saharan Africa, Eastern Europe and Oceania, combined with gradual improvements in agricultural practice and management (including livestock). However, such development schemes – that could also generate substantial additional income for rural regions that can export biomass – are uncertain, and implementation depends on many factors such as trade policies, agricultural policies, the establishment of sustainability frameworks such as certification, and investments in infrastructure and conventional agriculture (see also Faaij & Domac, 2006).

In addition, the use of degraded lands for biomass production (as in reforestation schemes: 8–110 EJ) could contribute significantly. Although biomass production with such low yields generally results in more expensive biomass supplies, competition with food production is almost absent and various co-benefits, such as the regeneration of soils (and carbon storage), improved water retention, and protection from erosion may also offset some of the establishment costs. An important example of such biomass production schemes at the moment is the establishment of jatropha crops (oil seeds, also spelled jathropa) on marginal lands.

Biomass residues and wastes. Table 11.2 also depicts the energy potentials in residues from forestry (12–74 EJ/yr) and agriculture (15–70 EJ/yr) as well as waste (13 EJ/yr). Those biomass resource categories are largely available before 2030, but also somewhat uncertain. The uncertainty comes from possible competing uses (for example, the increased use of biomaterials such as fibreboard production from forest residues and the use of agro-residues for fodder and fertilizer) and differing assumptions about the sustainability criteria deployed with respect to forest management and agriculture intensity. The current energy potential of waste is approximately 8 EJ/yr, which could increase to 13 EJ in 2030. The biogas fuel potentials from waste, landfill gas and digester gas are much smaller.

Synthesis of biomass supply & demand

A proper comparison of demand and supply is not possible since most of the estimates for supply relate to 2050. Demand has been assessed for 2030. Taking this into account, the lower end of the biomass supply (estimated at about 125 EJ/yr) exceeds the lower estimate of biomass demand (estimated

Table 11.2: *Biomass supply potentials and biomass demand in EJ based on Chapters 4 to 10*

Sector	Supply	Demand			
	Biomass supplies to 2050	Energy supply biomass demand 2030	Transport biomass demand 2030	Built environment	Industry
Agriculture				Relevant, in particular in developing countries as cooking fuel	Sugar industry significant. Food & beverage industry. No quantitative estimate on use for new biomaterials (e.g. bio-plastics) not significant for 2030.
Residues	15-70				
Dung	5-55				
Energy crops on arable land and pastures	20-300				
Crops on degraded lands	60-150				
Forestry	12-74	Key application	Relevant for second-generation biofuels	Relevant	
Waste	13	Power and heat production	Possibly via gasification	Minimal	Cement industry
Industry	Process residues				Relevant; paper & pulp industry
Total supply primary biomass	125-760				
Total demand primary biomass	70-130	28-43 (electricity) Heat excluded	45-85	Relevant (currently several dozens of EJ; additional demand may be limited)	Significant demand; paper & pulp and sugar industry use own process residues; additional demand expected to be limited

at 70 EJ/yr). However, demand does not include estimates of domestic biomass use (such as cooking fuel, although that use may diminish over time depending on development pathways in developing countries), increased biomass for production of heat (although additional demand in this area may be limited) and biomass use in industry (excluding the possible demand of biomass for new biomaterials). It seems that this demand can be met by biomass residues from forestry, agriculture, waste and dung and a limited contribution from energy crops. Such a 'low biomass demand' pathway may develop from the use of agricultural crops with more limited potentials, lower GHG mitigation impact and less attractive economic prospects, in particular in temperate climate regions. The major exception here is sugar-cane-based ethanol production.

The estimated high biomass demand consists of an estimated maximum use of biomass for power production and the constrained growth of production of biofuels when the WEO projections are taken into consideration (25 EJ/yr biofuels and about 40 EJ/yr primary biomass demand). Total combined demand for biomass for power and fuels adds up to about 130 EJ/yr. Clearly, a more substantial contribution from energy crops (perhaps in part from degraded lands, for example producing jatropha oil seeds) is required to cover total demand of this magnitude, but this still seems feasible, even for 2030; the low-end estimate for energy crops for agricultural land is 50 EJ/yr, which is in line with the 40 EJ/yr primary projected demand for biofuels.

However, as was also acknowledged in the WEO, the demand for biomass as biofuels in around 2030 will depend in particular on the commercialization of second-generation biofuel technologies (i.e. the large-scale gasification of biomass for the production of synfuels as Fischer-Tropsch diesel, methanol or DME, and the hydrolysis of lignocellulosic biomass for the production of ethanol). According to Hamelinck and Faaij (2006), such technologies offer competitive biofuel production compared to oil priced at between 40–50 US$/barrel (assuming biomass prices of around 2 US$/GJ). In Chapter 5, Figure 5.9 (IEA, 2006b), however, assumes higher biofuel costs. Another key option is the wider deployment of sugar cane for ethanol production, especially on a larger scale using state-of-the art mills, and possibly in combination with hydrolysis technology and additional ethanol production from bagasse (as argued by Moreira, 2006 and other authors). The availability of such technologies before 2020 may lead to an acceleration of biofuel production and use, even before 2030. Biofuels may therefore become the most important demand factor for biomass, especially in the longer term (i.e. beyond 2030).

A more problematic situation arises when the development of biomass resources (both residues and cultivated biomass) fails to keep up with demand. Although the higher end of biomass supply estimates (2050) is well above the maximum projected biomass demand for 2030, the net availability of biomass in 2030 will be considerably lower than the 2050 estimates. If biomass supplies fall short, this is likely to lead to significant price increases for raw materials. This would have a direct effect on the economic feasibility of various biomass applications. Generally, biomass feedstock costs can cover 30–50% of the production costs of secondary energy carriers, so increasing feedstock prices will quickly reduce the increase in biomass demand (but simultaneously stimulate investments in biomass production). To date, there has been very little research into interactions of this kind, especially at the global scale.

Comparing mitigation estimates for top-down and bottom-up modelling is not straightforward. Bottom-up mitigation responses are typically more detailed and derived from more constrained modelling exercises. Cost estimates are therefore in partial equilibrium in that input and output market prices are fixed, as may be key input quantities such as acreage or capital. Top-down mitigation responses consider more generic mitigation technologies and changes in outputs and inputs (such as shifts from food crops or forests to energy crops) as well as changes in market prices (such as land prices as competition for land increases). In addition, current top-down models optimistically assume the simultaneous global adoption of a coordinated climate policy with an unconstrained, or almost unconstrained, set of mitigation options across sectors. A review of top-down studies (Chapter 3 data assembled from Rose *et al.* (2007) and US CCSP (2006)) results in a range for total projected biomass use over all cost categories of 20 to 79 EJ/yr (defined as solid and liquid, requiring a conversion ratio from primary biomass to fuels). This is, on average, half the range for estimates obtained via bottom-up information from the various chapters.

Given the relatively small number of relevant scenario studies available to date, it is fair to say that the role of biomass in long-term stabilization (beyond 2030) will be very significant but that it is subject to relatively large uncertainties. Further research is required to improve our insight into the potential. A number of key factors influencing biomass mitigation potential are worth noting: the baseline economic growth and energy supply alternatives, assumptions about technological change (such as the rate of development of cellulosic ethanol conversion technology), land use competition, and mitigation alternatives (overall and land-related).

Given the lack of studies of how biomass resources may be distributed over various demand sectors, we do not suggest any allocation of the different biomass supplies to various applications. Furthermore, the net avoidance costs per ton of CO_2 of biomass usage depend on a wide variety of factors, including the biomass resource and supply (logistics) costs, conversion costs (which in turn depend on the availability of improved or advanced technologies) and reference fossil fuel prices, most notably of oil.

11.3.1.5 Estimates of mitigation potentials from Chapters 4 to 10

Table 11.3 uses the procedures outlined above to bring together the estimates for the economic potentials for GHG mitigation from Chapters 4 to 10. It was not possible to break down the potential into the desired cost categories for all sectors. Where appropriate, then, the cells in the table have been merged to account for the fact that the numbers represent the total of two cost categories. Only the potentials in the cost categories up to 100 US$/t$CO_2$-eq are reported here. Some of the chapters also report numbers for the potential in higher cost categories. This is the case for Chapter 5 (transport) and Chapter 8 (agriculture).

Table 11.3 suggests that the economic potential for reducing GHG emissions at costs below 100 US$/t$CO_2$ ranges[7] from 16 to 30 GtCO_2-eq. The contributions of each sector to the totals are in the order of magnitude 2 to 6 GtCO_2-eq (mid-range numbers), except for the waste sector (0.4 to 1 GtCO_2-eq). The mitigation potentials at the lowest cost are estimated for the buildings sector. Based on the literature assessment presented in Chapter 6 it can be concluded that over 80% of the buildings potential can be identified at negative cost. However, significant barriers need to be overcome to achieve these potentials. See Chapter 6 for more information on these barriers.

In all sectors, except for the transport sector, the highest economic potential for emission reduction is thought to be in the non-OECD/EIT region. In relative terms, although it is not possible to be exact because baselines across sectors are different, the emission reduction options at costs below 100 US$/t$CO_2$-eq are in the range of 30 to 50% of the totalled baseline. This is an indicative figure as it is compiled from a range of different baselines.

A number of comments should be made on the overview presented in Table 11.3.

First, a set of emission reduction options have been excluded from the analysis, because the available literature did not allow for a reliable assessment of the potential.[8]

- Emission reduction estimates of fluorinated gases from energy supply, transport and buildings are not included in the sector mitigation potentials from Chapters 4 to 6. For these sectors, the special IPCC report on ozone and climate (IPCC & TEAP, 2005) reported a mitigation potential for HFCs of 0.44 GtCO_2-eq for the year 2015 (a mitigation potential of 0.46 GtCO_2-eq was reported for CFCs and HCFCs).

7 Note that the range is found by aggregating the low or the high potentials per sector. As the errors in the potentials by sector are not correlated, counting up the errors using error propagation rules would lead to a range about half this size. However, given all the uncertainties, and in order to make statements with enough confidence, the full range reported here is used.

8 As indicated in the notes to Table 11.1, bog fires in the forestry sector have also been excluded from the emissions and therefore from the reduction potential as well. The emissions may be significant (in the order of 3 GtCO2-eq), see Chapter 1.

Table 11.3: *Estimated economic potentials for GHG mitigation at a sectoral level in 2030 for different cost categories using the SRES B2 and IEA World Energy Outlook (2004) baselines*

Sector	Mitigation option[a)]	Region	Economic potential <100 US$/$tCO_2$-eq[c)]		Economic potential in different cost categories[d), e)]			
			Cost cat. US$/$tCO_2$-eq		<0	0-20	20-50	50-100
			Cost cat. US$/tC-eq		<0	0-73	73-183	183-367
			Low	*High*				
			Gt CO_2-eq					
Energy supply[e)] (see also 4.4)	All options in energy supply excl. electricity savings in other sectors	OECD	0.90	1.7	0.9		0.50	0
		EIT	0.20	0.25	0.15		0.06	0
		Non-OECD/EIT	1.3	2.7	0.80		0.90	0.35
		Global	2.4	4.7	1.9		1.4	0.35
Transport[b), e), g)] (see also 5.6)	Total	OECD	0.50	0.55	0.25	0.25	0	0
		EIT	0.05	0.05	0.03	0	0	0.02
		Non-OECD/EIT	0.15	0.15	0.10	0.03	0.02	0
		Global[b)]	1.6	2.5	0.35	1.4	0.15	0.15
Buildings (see also 6.4)[f), h)]	Electricity savings	OECD	0.8	1.0	0.95	0.00	0	
		EIT	0.2	0.3	0.25	0	0	
		Non-OECD/EIT	2.0	2.5	2.1	0.05	0.05	
	Fuel savings	OECD	1.0	1.3	0.85	0.15	0.15	
		EIT	0.6	0.8	0.2	0.15	0.35	
		Non-OECD/EIT	0.7	0.8	0.65	0.10	0.01	
	Total	OECD	1.8	2.3	1.8	0.15	0.15	
		EIT	0.9	1.1	0.45	0.15	0.35	
		Non-OECD/EIT	2.7	3.3	2.7	0.15	0.10	
		Global	5.4	6.7	5.0	0.50	0.60	
Industry (see also 7.5)	Electricity savings	OECD	0.30		0.07		0.07	0.15
		EIT	0.08		0.02		0.02	0.040
		Non-OECD/EIT	0.45		0.10		0.10	0.25
	Other savings, including non-CO_2 GHG	OECD	0.35	0.90	0.30		0.25	0.05
		EIT	0.20	0.45	0.08		0.25	0.02
		Non-OECD/EIT	1.2	3.3	0.50		1.7	0.08
	Total	OECD	0.60	1.2	0.35		0.35	0.20
		EIT	0.25	0.55	0.10		0.25	0.06
		Non-OECD/EIT	1.6	3.8	0.60		1.8	0.30
		Global	2.5	5.5	1.1		2.4	0.55
Agriculture (see also 8.4)	All options	OECD	0.45	1.3	0.30		0.20	0.30
		EIT	0.25	0.65	0.15		0.10	0.15
		Non-OECD/EIT	1.6	4.5	1.1		0.75	1.2
		Global	2.3	6.4	1.6		1.1	1.7
Forestry (see also 9.4)	All options	OECD	0.40	1.0	0.01	0.25	0.30	0.25
		EIT	0.09	0.20	0	0.05	0.05	0.05
		Non-OECD/EIT	0.75	3.0	0.15	0.90	0.55	0.35
		Global	1.3	4.2	0.15	1.1	0.90	0.65
Waste (see also 10.4)	All options	OECD	0.10	0.20	0.10	0.06	0.00	0.00
		EIT	0.10	0.10	0.05	0.05	0.00	0.00
		Non-OECD/EIT	0.20	0.70	0.25	0.07	0.10	0.04
		Global	0.40	1.0	0.40	0.18	0.10	0.04
All sectors[i)]	All options	OECD	4.9	7.4	2.2	2.1	1.3	1.1
		EIT	1.8	2.8	0.55	0.65	0.50	1.0
		Non-OECD/EIT	8.3	16.8	3.3	3.6	4.1	2.4
		Global	15.8	31.1	6.1	7.4	6.0	4.5

Notes:
a) Several reduction options are not included due to limited literature sources. This underestimation could be about 10–15%; see below.
b) For transport, the regional data by cost category do not add up to the global potential: regional (cost) distribution is available for LDV only. Due to the lack of international agreement about the regional allocation of aviation emissions, only global cost distributions are available for aviation. A lack of data means that only global figures are presented for biofuels, and not cost distribution.
c) The ranges indicated by the potential are derived differently for each chapter. See underlying chapters for more information.
d) The economic potential figures per cost category are mid-range numbers.
e) The mitigation potential for the use of biomass is allocated to the transport and power sector. See the discussion on biomass energy in 11.3.1.4.
f) For the buildings sector the literature mainly focuses on low-cost mitigation options, and the potential in high-cost categories may be underestimated. The zero may represent an underestimation of the emissions.
g) The '0' means zero, 0.00 means a value below 5 Mton.
h) The electricity savings in the end-use sectors Buildings and Industry are the high estimates. The electricity savings would be significantly lower if the order of measurement were to be reversed; the substitution potential in the energy sector would have been assessed before electricity savings (see Appendix 11.1).
i) The tourism sector is included in the buildings and the transport sector.

- The potential for combined generation of heat and power in the energy supply sector has not added to the other potentials as it is uncertain (see Section 4.4.3). IEA (2006a) quotes a potential here of 0.2 to 0.4 $GtCO_2$-eq.
- The potential emissions reduction for coal mining and gas pipelines has not been included in the reductions from the power sector. De Jager *et al.* (2001) indicated that the CH_4 emissions from coal mining in 2020 might be in the order of 0.65 $GtCO_2$-eq. Reductions of 70 to 90% with a penetration level of 40% might be possible, resulting for 2020 in the order of 0.20 $GtCO_2$-eq. Higher reduction potentials of 0.47 $GtCO_2$-eq for CH_4 from coal mining have also been mentioned (Delhotal *et al.*, 2006).
- Emission reductions in freight transport (heavy duty vehicles), public transport, and marine transport have not been included. In the transport sector, only the mitigation potential for light duty vehicle efficiency improvement (LDV), air planes and biofuels for road transport has been assessed. Because LDV represents roughly two-thirds of transportation by road, and because road transportation represents roughly three-quarters of transport as a whole (air, water, and rail transport represent roughly 11, 9 and 3 percent of overall transport respectively), the estimate for LDV broadly reflects half of the transport activity for which a mitigation potential of over 0.70 $GtCO_2$-eq is reported. In the case of marine transport, the literature studies discussed in Section 5.3.4 indicate that large reductions are possible compared to the current standard but this might not be significant when comparing to a baseline. See also Table 5.8 for indicative potentials for some of the options.
- Non-technical options in the transport sector, like speed limits and changes in modal split or behaviour changes, are not taken into account (an indication of the order of magnitude for Latin American cities is given in Table 5.6).
- For the buildings sector, most literature sources focused on low-cost mitigation options and so high-cost options are less well represented. Behavioural changes in the buildings sector have not been included; some of these raise energy demand, examples being rebound effects from improvements in energy efficiency.[9]
- In the industry sector, the fuel savings have only been estimated for the energy-intensive sectors representing approximately 50% of fuel use in manufacturing industry.
- The TAR stated an emission reduction estimate of 2.20 $GtCO_2$-eq in 2020 for material efficiency. Chapter 7 does not include material efficiency, except for recycling for selected industries, in the estimate of the industrial emission reduction potential. To avoid double counting, the TAR estimate should not be added to the potentials of Chapter 7. However, it is likely that the potential for material efficiency significantly exceeds that for recycling for selected industries only given in Chapter 7.

In conclusion, the options excluded represent significant potentials that justify future analysis. These options represent about 10 to 15% of the potential reported in Table 11.3; this magnitude is not such that the conclusions of the bottom-up analysis would change substantially.

Secondly, the chapters identified a number of key sensitivities that have not been quantified. Note that the key sensitivities are different for the different sectors.

In general, higher energy prices will have some impact on the mitigation potentials presented here (i.e. those with costs below 100 US\$/tCO_2-eq), but the impact is expected to be generally limited, except for the transport sector (see below). No major options have been identified exceeding 100 US\$/ tCO_2-eq that could move to below 100 US\$/tCO_2-eq. However, this is only true of the fairly static approach presented here. The costs and potential of technologies in 2030 may be different if energy prices remain high for several decades compared to the situation if they return to the levels of the 1990s. High energy prices may also impact the baseline since the fuel mix will change and lower emissions can be expected. Note that options in some areas, such as agriculture and forestry and non-CO_2 greenhouse gases (about one third of the potential reported), are not affected by energy prices, or much less so.

More specifically, an important sensitivity for the transport sector is the future oil price. The total potential for the LDV in transport increases by 7% as prices rise from 30 to 60 US\$/ barrel. However, the potential at costs <0 US\$/tCO_2 increases much more – by almost 90% – because of the fuel saving effect. (See Section 5.4.2).

- Discount rates that formed the basis of the analysis are – as reported in the individual chapters – in the range of 3 to 10%, with the majority of studies using the lower end of this range. Lower discount rates (e.g. 2%) would imply some shift to lower cost ranges, without substantially affecting the total potential. Moving to higher discount rates would have a particular impact on the potential in the highest cost range, which makes up 15 to 20% of the total potential.
- Agriculture and forestry potential estimates are based on long-term experimental results under current climate conditions. Given moderate deviations in the climate expected by 2030, the mitigation estimates are considered quite robust.

Thirdly, potentials with costs below zero US\$/tCO_2-eq are presented in Table 11.3. The potential at negative cost is considerable. There is evidence from business studies showing the existence of mitigation options at negative cost (for example, The Climate Group, 2005). For a discussion of the reasons for mitigation options at negative costs, see IPCC (2001), Chapters 3 and 7; and Chapters 2 and 6, and Section 11.6 of this report.

9 Greening et al. (2000, p.399), in a survey of the rebound effect (in which efficiency improvements lead to more use of energy), remark that ‘rebound is not high enough to mitigate the importance of energy efficiency as a way of reducing carbon emissions. However, climate policies that rely only on energy efficiency technologies may need reinforcement by market instruments such as fuel taxes and other incentive mechanisms.’

These remarks do not affect the validity of the overall findings, i.e. that the economic potential at costs below 100 US$/t$CO_2$-eq ranges from 16 to 30 GtCO_2-eq. However, they reflect a basic shortcoming of the bottom-up analysis. For individual countries, sectors or gases, the literature includes excellent bottom-up analysis of mitigation potentials. However, they are usually not comparable and their coverage of countries/sectors/gases is limited.

The following gaps in the literature have been identified. Firstly, there is no harmonized integrated standard for bottom-up analysis that compares all future economic potentials. Harmonization is considered important for, *inter alia*, target years, discount rates, price scenarios. Secondly, there is a lack of bottom-up estimates of mitigation potentials, including those for rebound effects of energy-efficiency policies for transport and buildings, for regions such as many EIT countries and substantial parts of the non-OECD/EIT grouping.

11.3.1.6 Comparison with the Third Assessment Report (TAR)

Table 11.4 compares the estimates in this report (AR4) for 2030 with those from the TAR for 2020, which were evaluated at costs less than 27 US$/t$CO_2$-eq (100 US$/tCO_2-eq). The last column shows the AR4 estimates for potentials at costs of less than 20 US$/t$CO_2$-eq, which are more comparable with those from the TAR. Overall, the estimated bottom-up economic potential has been revised downwards compared to that in the TAR, even though this report has a longer time horizon than the TAR. Only the buildings sector has been revised upwards in this cost category. For the forestry sector, the economic potential now is significantly lower compared to TAR. However, the TAR numbers for the forestry potential were not specified in terms of cost levels and are more comparable with the < 100 US$/t$CO_2$-eq potential in this report. Even then, they are much higher because they are based on top-down global forest models. These models generally give much higher values then bottom-up studies, as reflected in Chapter 9 of this report. The industry sector is estimated to have a lower potential at costs below 20 US$/t$CO_2$-eq, partly due to a lack of data available for use in the AR4 analyses. Only electricity savings have been included for light industry. In addition, the potential for CHP was allocated to the industry sector in the TAR and was not covered in this report. The most important difference between the TAR and the current analysis is that, in the TAR, material efficiency in a wide sense has been included in the industry sector. In this report, only some aspects of material efficiency have been included, namely in Chapter 7.

The updated estimates might be expected to be higher due to:
- The greater range of economic potentials, extending up to 100 US$/tCO2, compared to less than 27.3 US$/t$CO_2$ (100 US$/tC) in the TAR;
- The different time frame: 2030 compared to 2020 in the TAR.

However, the overall estimated bottom-up economic potential has been revised downwards somewhat, compared to that in the TAR, especially considering that the AR4 estimates allow for about five more years of technological change. Part of the difference is caused by the lower coverage of mitigation options up to 2030 in the AR4 literature.

11.3.1.7 Conclusions of bottom-up potential estimates

When comparing the emission reduction potentials as presented in Table 11.4 with the baseline emissions, it can be concluded that the total economic potential at costs below 20 US$/t$CO_2$-eq ranges from 15 to 30% of the total added-up baseline.

Table 11.4: *Comparison of potential global emission reductions for 2030 with the global estimates for 2020 from the Third Assessment Report (TAR) in GtCO_2-eq*

Sector	Options	TAR potential emissions reductions by 2020 at costs <27.3 US$/t$CO_2$ a)		AR4 potential emissions reductions by 2030 at costs <20 US$/t$CO_2$ b)	
	Estimate	Low	High	Low	High
Energy supply and conversion		1.3	2.6	1.2	2.4
Transport	CO_2 only	1.1	2.6	1.3	2.1
Buildings	CO_2 only	3.7	4.0	4.9	6.1
Industry	CO_2 only			0.70	1.5
- energy efficiency		2.6	3.3		
- material efficiency		2.2	2.2		
	non-CO_2	0.37	0.37		
Agriculture c)	C-sinks and non CO_2 c)	1.3	2.8	0.30	2.4
Forestry		(11.7) d)	(11.7)	0.55	1.9
Waste	CH_4 only	0.73	0.73	0.35	0.85
Total		13.2 e)	18.5 e)	9.3	17.1

Notes:
a) The TAR range excludes options with costs above 27.3 US$/t$CO_2$ (100 US$/tC) (except for non-$CO_2$ GHGs), and options that will not be adopted through the use of generally accepted policies (p. 264). Differences are due to rounding off.
b) This is the sum of the potential reduction at negative costs and below 20 US$/tCO2. See, however, notes to Table 11.2.
c) Note that TAR estimates are for non-CO_2 emissions only. The AR4 estimates also include soil C sequestration (about 90% of the mitigation potential).
d) TAR copied the estimate of Special Report on LULUCF for 2010, which was seen as a technical potential.
e) The 2020 emissions for the SRES B2 baseline was estimated at 49.5 Gton CO2-eq (IPCC, 2000)

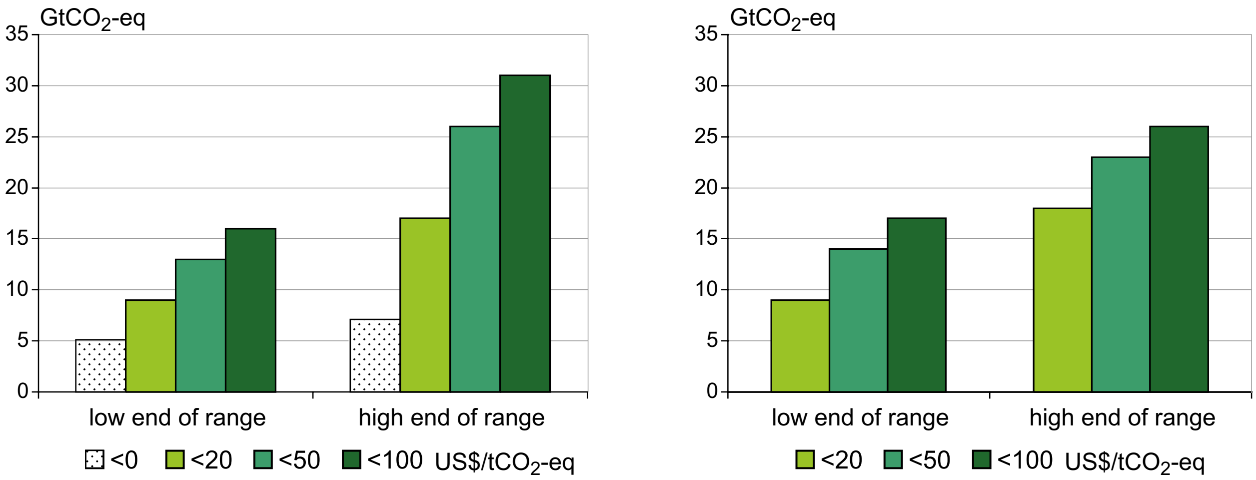

Figure 11.3: *Economic mitigation potential in different cost categories as compared to the baseline*

Notes: The ranges reported in Tables 3.13 and 3.14 were used for comparison for the top-down studies. 'High' and 'low' refer to the high and low ends of the economic potential range reported.

The economic potential up to 100 US$/t$CO_2$-eq is about 30 to 50% of emissions in 2030. There is medium evidence for these conclusions because, although a significant amount of literature is available, there are gaps and regional biases, and baselines are different. There is also medium agreement on these conclusions because there is literature for each sector with substantial ranges but the ranges may not capture all the uncertainties that exist. Although there are differences in relative mitigation potentials and specific mitigation costs between sectors (e.g. the buildings sector has a large share of low-cost options), it is clear that the total mitigation potential is spread across the various sectors. Substantial emission reductions can only be achieved if most of the sectors contribute to the emission reduction. In addition, there are barriers that need to be overcome if these potentials are to materialize.

11.3.2 Comparing bottom-up and top-down sectoral potentials for 2030

Table 11.5 and Figure 11.3 bring together the ranges of economic potentials synthesized from Chapters 4 to 10, as discussed in 11.3.1, with the ranges of top-down sectoral estimates for 2030 presented in Chapter 3. The bottom-up estimates are shown with the potentials from end-use electricity savings attributed (1) to the end-use sectors, i.e. to the buildings and industry sectors primarily responsible for the electricity use and (2) upstream, at the point of emission to the energy supply sector. The top-down ranges are provided by an analysis of the data from multi-gas studies for 2030 reported in Section 3.6. A relationship has been estimated between the absolute reductions in total GHGs and the carbon prices required to achieve them (see Appendix 3.1). Ranges for mitigation potential have been calculated for a 68% confidence interval for carbon prices at 20 and 100 US$(2000)/t$CO_2$-eq. The ranges are shown in the last two columns of Table 11.5.

The ranges of bottom-up and top-down aggregate estimates of potentials overlap substantially under all cost ceilings except for the no-regrets bottom-up options. This contrasts with the comparison in the TAR, where top-down costs were higher. It is not the case that bottom-up approaches systematically generate higher abatement potentials. This change comes largely from lower costs in the top-down models, because some have introduced multi-gas abatement and have introduced more bottom-up features, such as induced technological change, which also tend to reduce costs.

Two further points can be made with regard to the comparison of bottom-up and top-down results:

1) Sector definitions differ between top-down and bottom-up approaches. The sectoral data presented here are not fully comparable. The main difference is that the electricity savings are allocated to the power sector in the top-down models compared to the end-use sectors in Table 11.3. Both allocation approaches are presented in Table 11.5.
2) At a sector level however, there are some systematic and striking discrepancies:
   Energy supply. The top-down models indicate a higher emission reduction. This can be explained in part by differences in the mitigation options that are included in the top-down models and not included in the bottom-up approach. Examples are: reductions in extraction and distribution, reductions of other non-CO_2 emissions, and reductions through the increased use of CHP. Further, different estimates of the inertia of the substitution are expected to play a role. In bottom-up estimates, fuel substitution is assumed only after end-use savings whereas top-down models adopt a more continuous approach. Finally, the top-down estimates include the effects of energy savings in other sectors and structural changes. For example, a reduction in oil use also implies a reduction in emissions from refineries. These effects are excluded from the bottom-up estimates.

Table 11.5.: *Economic potential for sectoral mitigation by 2030: comparison of bottom-up and top-down estimates*

Chapter of report	Estimate	Sector-based ('bottom-up') potential by 2030 ($GtCO_2$-eq/yr)				Economy-wide model ('top-down') snapshot of mitigation by 2030 ($GtCO_2$-eq/yr)	
		Downstream (indirect) allocation of electricity savings to end-use sectors		Point-of-emissions allocation (emission savings from end-use electricity savings allocated to energy supply sector)			
		Low	High	Low	High	Low	High
		'Low cost' emission reductions: carbon price <20 US$/$tCO_2$-eq					
4	Energy supply	1.2	2.4	4.4	6.4	3.9	9.7
5	Transport	1.3	2.1	1.3	2.1	0.1	1.6
6	Buildings	4.9	6.1	1.9	2.3	0.3	1.1
7	Industry	0.7	1.5	0.5	1.3	1.2	3.2
8	Agriculture	0.3	2.4	0.3	2.4	0.6	1.2
9	Forestry	0.6	1.9	0.6	1.9	0.2	0.8
10	Waste	0.3	0.8	0.3	0.8	0.7	0.9
11	Total	9.3	17.1	9.1	17.9	8.7	17.9
		'Medium cost' emission reductions: carbon price <50 US$/$tCO_2$-eq					
4	Energy supply	2.2	4.2	5.6	8.4	6.7	12.4
5	Transport	1.5	2.3	1.5	2.3	0.5	1.9
6	Buildings	4.9	6.1	1.9	2.3	0.4	1.3
7	Industry	2.2	4.7	1.6	4.5	2.2	4.3
8	Agriculture	1.4	3.9	1.4	3.9	0.8	1.4
9	Forestry	1.0	3.2	1.0	3.2	0.2	0.8
10	Waste	0.4	1.0	0.4	1.0	0.8	1
11	Total	13.3	25.7	13.2	25.8	13.7	22.6
		'High cost' emission reductions: carbon price <100 US$/$tCO_2$-eq					
4	Energy supply	2.4	4.7	6.3	9.3	8.7	14.5
5	Transport	1.6	2.5	1.6	2.5	0.8	2.5
6	Buildings	5.4	6.7	2.3	2.9	0.6	1,5
7	Industry	2.5	5.5	1.7	4.7	3	5
8	Agriculture	2.3	6.4	2.3	6.4	0.9	1.5
9	Forestry	1.3	4.2	1.3	4.2	0.2	0.8
10	Waste	0.4	1.0	0.4	1	0.9	1.1
11	Total	15.8	31.1	15.8	31.1	16.8	26.2

Sources: Tables 3.16, 3.17 and 11.2 and Edenhofer et al., 2006
See notes to Tables 3.16, 3.17 and 11.2 and Appendix 11.1.

Buildings. Top-down models give estimates of reduction potentials from the buildings sector that are lower than those from bottom-up assessments. This is because the top-down models look only at responses to price signals, whereas most of the potential in the buildings sector is thought to be from 'negative cost' measures that would be primarily realized through other kinds of interventions (such as buildings or appliance standards). Top-down models assume that the regulatory environments of 'reference' and 'abatement' cases are similar, so that any negative cost potential is either neglected or assumed to be included in baseline.

Agriculture and forestry. The estimates from bottom-up assessments were higher than those found in top-down studies, particularly at higher cost levels. These sectors are often not covered well by top-down models due to their specific character. An additional explanation is that the data from the top-down estimates include additional deforestation (negative mitigation potential) due to biomass energy plantations. This factor is not included in the bottom-up estimates.

Industry. The top-down models generate higher estimates of reduction potentials in industry than the bottom-up assessments. One of the reasons could be that top-down models allow for product substitution, which is often excluded in bottom-up sector analysis; equally, top-down models may have a greater tendency to allow for innovation over time.

The overall bottom-up potential, both at low and high carbon prices, is consistent with that of 2030 results from top-down models as reported in Chapter 3, Section 3.6.2 for a limited set of models. For carbon prices <20 US$/$tCO_2$-eq, the ranges are 10–17 $GtCO_2$-eq/yr for bottom-up, as opposed to 9–18 $GtCO_2$-eq/yr for top-down studies. For carbon prices <50 US$/$tCO_2$-eq, the ranges are 14–25 $GtCO_2$-eq/yr for bottom-up versus 14–23 $GtCO_2$-eq/yr for top-down studies. For carbon prices <100 US$/$tCO_2$-eq the ranges are 16–30 $GtCO_2$-eq/yr and 17–26 $GtCO_2$-eq/yr for bottom-up and top-down respectively. As explained above, the differences between bottom-up and top-down are larger at the sector level.

11.3.3 Studies of interactions between energy supply and demand

This section looks at literature dealing specifically with the modelling of interactions between energy supply and demand. It first considers the carbon content of electricity, a crucial feature of the cross-sectoral aggregation of potentials discussed above, and then the effect of mitigation on energy prices. The studies emphasize the dependence of mitigation potentials from end-use electricity savings on the generation mix.

11.3.3.1 The carbon content of electricity

As discussed above, there are many interactions between CO_2 mitigation measures in the demand and supply of energy. Particularly in the case of electricity, consumers are unaware of the types and volumes of primary energy required for generating electricity. The electricity producer determines the power generation mix, which depends on the load characteristics. The CO_2 mitigation measures not only affect the generation mix (supply side) through the load characteristics. They are also influenced by the price.

Iwafune *et al.* (2001a; 2001b; 2001c), and Kraines *et al.* (2001) discuss the effects of the interactions between electricity supply and demand sectors in the Virtual Tokyo model. Demand-side options and supply-side options are considered simultaneously, with changes in the optimal mix in power generation reflecting changes in the load profile caused by the introductions of demand-side options such as the enhanced insulation of buildings and installation of photovoltaic (PV) modules on rooftops. The economic indicators used for demand-side behaviours are investment pay-back time and marginal CO_2 abatement cost. Typical results of Iwafune *et al.* (2001a) are that the introduction of demand-side measures reduces electricity demand in Tokyo by 3.5%, reducing CO_2 emissions from power supply by 7.6%. The CO_2 emission intensity of the reduced electricity demand is more than two times higher than the average CO_2 intensity of electricity supply because reductions in electricity demands caused by the saving of building energy demand and/or the installation of PV modules occur mainly in daytime when more carbon-intensive fuels are used. A similar 'wedge' – in this case between the average carbon intensity of electricity supply and the carbon value of electricity savings – was found, in the UK system, to depend upon the price of EU ETS allowances, with high ETS prices increasing the carbon value of end-use savings by around 40% as coal is pushed to the margin of power generation (Grubb and Wilde, 2005).

Komiyama *et al.* (2003) evaluate the total system effect in terms of CO_2 emission reduction by introducing co-generation (CHP, combined heat and power) in residential and commercial sectors, using a long-term optimal generation-mix model to allow for the indirect effects on CO_2 emissions from power generation. In a standard scenario, where the first technology to be substituted is oil-fired power, followed later by LNG CC and IGCC, the installation of CHP reduces CO_2 emission in the total system. However, in a different scenario, the CO_2 reduction effect of CHP introduction may be substantially lower. For example, the effect is negligible when highly efficient CCGTs (combined cycle gas turbines) are dominant at baseline and replaced by CHP. Furthermore, in the albeit unlikely case of nuclear power being competitive at baseline but replaced by CHP, the total CO_2 emission from the energy system increases with CHP installation. These results suggest that the CO_2 reduction potential associated with the introduction of CHP should be evaluated with caution.

11.3.3.2 The effects of rising energy prices on mitigation

Price responses to energy demand can be much larger when energy prices are rising than when they are falling, but responses in conventional modelling are symmetric. The mitigation response to policy may therefore be much larger when energy prices are rising. This phenomenon is addressed in literature about asymmetrical price responses and the effects of technological change (Gately and Huntington, 2002; Griffin and Shulman, 2005). Bashmakov (2006) also argues for asymmetrical responses in the analysis of what is called the economics of constants and variables: the existence of very stable energy costs to income proportions, which can be observed over the longer period of statistical observations in many countries. He argues that there are thresholds for total energy costs such as a ratio of GDP or gross output, and energy costs by transportation and residential sector as shares of personal income. If rising energy prices push the ratios towards the given thresholds, then the dynamics of energy-demand price responses are changed. The effect on real income can become sufficient to reduce GDP growth, mobility and the level of indoor comfort. Carbon taxes and permits become more effective the closer the ratio is to the threshold, so the same rates and prices generate different results depending on the relationship of the energy costs to income or of the gross output ratio to the threshold.

11.3.4 Regional cross-sectoral effects of greenhouse gas mitigation policies to 2025

Various estimates of cross-sectoral mitigation potential for specific regions have been published, usually as reports commissioned by governments. Unfortunately, however, the issue of attributing costs to cross-sectoral effects of greenhouse gas mitigation policies has not been reported extensively since the TAR, and literature on this topic is consequently sparse.

In one of the few studies to examine the sectoral effects of mitigation policies across countries, Meyer and Lutz (2002), using the COMPASS model, carried out a simulation of the effects of carbon taxes or the G7 countries, which include some of the biggest energy users. The authors assumed the introduction of a carbon tax of 1US$ per ton of CO_2 in 2001 in all of these countries, rising linearly to 10 US$ in 2010, with revenues used to lower social security contributions. Table 11.6

Table 11.6: *Impact on sectoral output of 1 US$/tCO$_2$ tax in 2001 rising to 10 US$/tCO$_2$ by 2010*

	USA	Japan	Germany	France	Italy	UK	Canada
	% difference from business-as-usual gross output in 2010						
Food processing	-2.02	-0.27	-0.32	-0.36	-0.29	-0.69	-1.83
Petroleum and coal products	-2.87	-0.33	-0.82	-0.50	-0.47	-2.42	-3.67
Iron and steel	-1.35	-0.28	-0.33	-0.45	-0.48	-0.82	-1.60
Machinery	-1.06	-0.22	-0.26	-0.29	-0.48	-0.72	-1.11
Motor vehicles	-1.41	-0.42	-0.33	-0.47	-0.40	-0.74	-1.92
Construction	-1.01	-0.02	-0.13	-0.21	-0.39	-0.78	-1.06
All industries	-1.74	-0.18	-0.32	-0.33	-0.35	-0.75	-1.71

Source: Meyer and Lutz (2002)

shows the effects on output: the decline in petroleum and coal products will be highest, with the effects on construction being mild. The scale of the effects differs substantially between countries, depending on the energy intensities of the economies and the carbon content of this energy, with effects on output being much larger in US and Canadian industries.

One major cross-sectoral study (EU DG Environment, 2001) brings together low-cost mitigation options and shows their effects across sectors and regions. It shows how a Kyoto-style target (8% reduction of EU GHGs below 1990/95 by 2010) can be achieved for the EU-15 member states with options costing less than 20 US$/tCO$_2$. The study assesses the direct and indirect outcomes using a top-down model (PRIMES) for energy-related CO$_2$ and a bottom-up model (GENESIS) for all other GHGs. The synthesis of the results is presented in Table 11.7. This multi-gas study considers all GHGs, but assumes that the JI and CDM flexibility instruments are not used. The study shows the wide variations in cost-effective mitigation across sectors. The largest reductions compared to the 1990/95 baselines are in the energy and energy-intensive sectors, whereas there is an increase of 25% in the transport sector compared to 1990/95 emissions. Note also the large reductions in methane and N$_2$O in the achievement of the overall target as shown in the lower panel of the table. The results are, however, dominated by bottom-up energy-engineering assumptions since PRIMES is a partial-equilibrium model. Consequently, the GDP effects of the options are not provided. These potentials can be compared to those at less than 20 US$/tCO$_2$ in Table 11.3 above for the sectoral synthesis for the OECD. The EU potentials are similarly concentrated in the buildings sector, but with a larger share for industry, and a lower one for transport, reflecting the high existing taxes on transport fuels in the EU.

Masui *et al.* (2005) report the effects of a tax and sectoral subsidy regime for Japan to achieve the Kyoto target by 2010, in which carbon tax revenues are used to subsidize additional investments to reduce greenhouse gases. The investment costs are shown in Table 11.8 for each sector. The table shows that about about 9 US$/tCO$_2$ (3,400 Japanese Yen/tC) will be required as carbon tax and most of the investment will be in energy-saving measures in the buildings sector (Residential and Commercial). The macro-economic effects for this study are reported in Section 11.4.3.4.

Schumacher and Sands (2006) model the response of German GHG emissions to various technology and carbon policy assumptions over the next few decades using the SGM model for Germany. Accounting for advanced technologies such as coal IGCC, NGCC, CCS, and wind power, they show that emission reductions can be achieved at substantially lower marginal abatement costs in the long run with new advanced electricity generating technologies in place. In a scenario assuming a carbon price of 50 US$/tCO$_2$ giving a 15% reduction of CO$_2$ below baseline by 2020, they show that, with the new and advanced technologies, the electricity sector would account for the largest share of emissions reductions (around 50% of total emissions reductions), followed by other (non-energy-intensive) industries and households. The effects on gross output are very uneven across sectors: energy transformation is 9% below base, but other industry, services and agriculture (and GDP) are 0.7% below base by 2050.

The effects of different policy mixes on sectoral outcomes are shown in the US EIA (2005) analysis of the National Commission on Energy Policy's (NCEP) 2004 proposals. These involve reductions in the US emissions in GHGs of about 11% by 2025 below a reference case, including an analysis of the cap-and-trade component, (involving a safety valve limiting the maximum cost of emissions permits to US$ (2003)8.50/tCO$_2$ through to 2025) and a no-safety-valve case (in which the cost rises to US$(2003) 35/tCO$_2$ and the GHG reduction to 15% by 2025). The effects on CO$_2$ emissions by broad sector are shown in Figure 11.4. Note that the NCEP scenario includes the cap-and-trade scheme (with a safety valve) shown separately in the figure and that the no-safety-valve scenario is additional to the NCEP scenario. The NCEP scenario includes substantial energy efficiency policies for transportation and buildings. This explains the relatively large contributions of these sectors in this scenario. The cap-and-trade schemes mainly affect the electricity sector, since the price of coal-fired generation rises relative to other generation technologies. For discussion of macro-economic estimates of mitigation costs for the US from this study and others, see Section 11.4.3.1.

Table 11.7: *Sectoral results from top-down energy modelling (PRIMES for energy-related CO_2) and bottom-up modelling (of non-CO_2 GHGs). The table shows the distribution of direct and total (direct and indirect) emissions of GHGs in 1990/1995, in the 2010 baseline and in the most cost-effective solution for 2010, where emissions are reduced by 8% compared to the 1990/1995 level. The top table gives the breakdown into sectors and the bottom table the breakdown into gases.*

EU-15 Emission breakdown per sector (top-down)	Direct emissions ($MtCO_2$-eq)					Direct and indirect emissions ($MtCO_2$-eq)				
	Emissions in 1990/95	Baseline emissions in 2010	Cost-effective objective 2010	Change from 1990/95	Change from 2010 baseline	Emissions in 1990/95	Baseline emissions in 2010	Cost-effective objective 2010	Change from 1990/95	Change from 2010 baseline
Energy supply[a),b)]	**1190**	**1206**	**1054**	**-11%**	**-13%**	**58**	**45**	**42**	**-27%**	**-6%**
CO_2 (energy-related)	1132	1161	1011	-11%	-13%					
auto-producers	124	278	229	85%	-18%					
utilities	836	772	667	-20%	-14%					
other	172	111	115	-33%	4%					
Non-CO_2	58	45	42	-27%	-6%	58	45	42	-27%	-6%
Non-CO_2 fossil fuel[c)]	**95**	**61**	**51**	**-46%**	**-16%**	**95**	**61**	**51**	**-46%**	**-16%**
Industry[b)]	894	759	665	-26%	-12%	1383	1282	1125	-19%	-12%
Iron and steel	196	158	145	-26%	-9%	253	200	183	-28%	-9%
Non-ferrous metals	24	22	13	-47%	-40%	66	42	30	-54%	-28%
Chemicals	243	121	81	-66%	-33%	362	257	201	-44%	-22%
Building Materials	201	212	208	3%	-2%	237	240	232	-2%	-3%
Paper and Pulp	29	22	20	-32%	-9%	69	106	92	34%	-13%
Food, drink, tobacco	46	35	26	-42%	-24%	89	107	91	2%	-15%
Other industries	155	189	172	11%	-9%	308	331	295	-4%	-11%
Transport	**753**	**984**	**946**	**26%**	**-4%**	**778**	**1019**	**975**	**25%**	**-4%**
CO_2 (energy-related)	735	919	887	21%	-4%	760	953	916	21%	-4%
road	624	741	724	16%	-2%	624	741	724	16%	-2%
train	9	2	2	-83%	-8%	34	36	31	-10%	-14%
aviation[d)]	82	150	135	65%	-10%	82	150	135	65%	-10%
inland navigation	21	27	26	26%	-2%	21	27	26	26%	-2%
Non-CO_2 (road)	18	65	59	222%	-10%	18	84	143	681%	70%
Households	**447**	**445**	**420**	**-6%**	**-6%**	**792**	**748**	**684**	**-14%**	**-9%**
Services	**176**	**200**	**170**	**-3%**	**-15%**	**448**	**500**	**428**	**-4%**	**-14%**
Agriculture	**417**	**398**	**382**	**-8%**	**-4%**	**417**	**398**	**382**	**-8%**	**-4%**
Waste	**166**	**137**	**119**	**-28%**	**-13%**	**166**	**137**	**119**	**-28%**	**-13%**
Total	**4138**	**4190**	**3807**	**-8%**	**-9%**	**4138**	**4190**	**3807**	**-8%**	**-9%**

Breakdown per gas	Emissions in 1990/95	Baseline emissions in 2010	Cost-effective objective 2010	Change from 1990/95	Change from 2010 baseline
CO_2 energy-related	3068	3193	2922	-5%	-8%
CO_2 other	164	183	182	11%	-1%
Methane	462	380	345	-25%	-9%
Nitrous oxide	376	317	282	-25%	-11%
HFCs	52	84	54	3%	-36%
PFCs	10	25	19	87%	-27%
SF6	5	7	3	-41%	-53%
Total	**4138**	**4190**	**3807**	**-8%**	**-9%**

Notes:

a) The direct CO_2 emissions of energy supply are allocated to the energy demand sectors in the right-hand part of the table representing direct and indirect emissions. Refineries are included in the energy supply sector.

b) Industrial boilers are allocated to industrial sectors.

c) Non-CO_2 GHG emissions from fossil fuel extraction, transport and distribution.

d) Due to missing data, emission data for aviation include international aviation, which is excluded in the IPCC inventory methodology.

Source: EU DG Environment, 2001.
http://europa.eu.int/comm/environment/enveco/climate_change/summary_report_policy_makers.pdf

Table 11.8: *Carbon tax rate and required additional investments for CO_2 abatement in Japan*

Sector	Subsidized measures and devices	Additional money grant (billion US$/yr)
Industrial sector	Boiler conversion control, High-performance motor, High-performance industrial furnace, Waste plastic injection blast furnace, LDF with closed LDG recovery, High-efficiency continuous annealing, Diffuser bleaching device, High-efficiency clinker cooler, Biomass power generation	0.95
Residential sector	High-efficiency air conditioner, High-efficiency gas stove, Solar water heater, High-efficiency gas cooking device, High-efficiency television, High-efficiency VCR, Latent heat recovery type water heater, High-efficiency illuminator, High-efficiency refrigerator, Standby electricity saving, Insulation	3.33
Commercial sector	High-efficiency electric refrigerator, High-efficiency air conditioner, High-efficiency gas absorption heat pump, High-efficiency gas boiler, Latent heat recovery type boiler, Solar water heater, High-efficiency gas cooking device, High-frequency inverter lighting with timer, High-efficiency vending machine, Amorphous transformer, Standby electricity saving, Ventilation with heat exchanger, Insulation	1.83
Transportation sector	High-efficiency gasoline private car, High-efficiency diesel car, Hybrid taxi, High-efficiency diesel bus, High-efficiency small-sized truck, High-efficiency standard-sized track	1.00
Forest management	Plantation, Weeding, Tree thinning, Multilayered thinning, Improvement of natural forests	1.84
Total		8.96
Required carbon tax rate (US$/t$CO_2$)		**8.7**

Source: Masui et al. (2005).

11.3.5 Portfolio analysis of mitigation options

Portfolio analysis in this context is the study of the mix of actions available to reduce emissions or adapt to climate change and to business in diversifying their investments against risk.

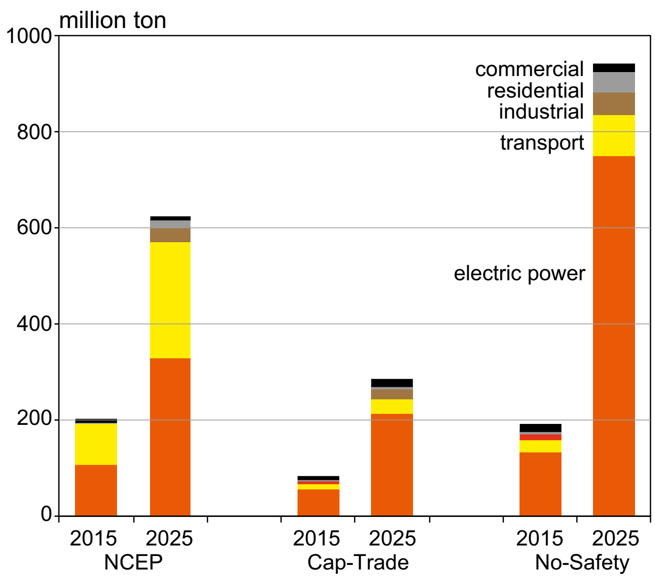

Figure 11.4: *Carbon dioxide reductions by sector in the NCEP, Cap-Trade, and No-Safety Cases, 2015 and 2025*

Notes: National Energy Modeling System, runs BING-ICE-CAP.D021005C BING-CAP.D021005A, and BING-NOCAP.D020805A. Note that NCEP includes technology mandates, and Cap-Trade is without technology mandates.

Source: US Energy Information Administration (EIA)(2005, p.15).

One issue is the allocation of GHG abatement across sectors or regions. Capros and Mantzos (2000) show that, within the EU, equal percentage reductions across sectors cost more than twice as much as a least cost distribution (which can be obtained by, for example, allowing trade between sectors); see Table 11.9. The table also shows the gains through international trading both across the EU and in Annex I, confirming the benefits reported in the TAR from a wide range of previous literature.

The reference case assumes that the Kyoto commitment is implemented separately by domestic action in each EU member state. The alternative reference case assumes that, within a member state, the overall emission reduction target of the burden-sharing agreement applies equally to each individual sector of the economy, with allocation evidently being more expensive than the least-cost approach in the reference case.

A related issue is the allocation of CO_2 emission reductions under Kyoto to sources in the EU Emissions Trading Scheme (EU ETS), as compared all non-ETS sources. Klepper and Peterson (2006), using a CGE model, conclude that ETS National Allocation Plans reduce the allowance price in the ETS below the implicit tax necessary for reaching the Kyoto targets in the non-ETS sectors, implying significant distortion. The limited use of CDM and JI to meet the allocations would result in a negative effect on welfare of close to 1% in 2012 relative to 'business as usual'; this assumes that EU Member States do not import more than 50% of their required reductions and that they do not import 'hot air'. Unrestricted trading in CDM and JI credits and allowances would result in an allocation where the Kyoto target can be met with hardly any welfare costs.

Table 11.9: *The effects of EU-wide and Annex B trading on compliance cost, savings and marginal abatement costs in 2010*

	Compliance cost	Savings against Reference Case		Savings against Alternative Reference Case		Marginal abatement cost (US$/$tCO_2$)	
	million US$	million US$	%	million US$	%	for sectors participating in EU-wide trading	for other sectors
No EU-wide trading							
Reference case: burden-sharing target implemented at least cost across sectors within a member state	9026	n.a.	n.a.	11482	56.0	n.a.	54.3
Alternative reference case: burden-sharing target allocated uniformly to all sectors within a member state	20508	-11482	-127.2	n.a.	n.a.	n.a.	125.8
EU-wide trading							
Energy suppliers	7158	1868	20.7	13350	65.1	32.3	45.3
Energy suppliers and energy-intensive industries	6863	2163	24.0	13645	66.5	33.3	43.3
All sectors	5957	3069	34.0	14551	71.0	32.6	32.6
Annex B trading: All sectors	4639	4387	48.6	15869	77.4	17.7	17.7

Notes: A negative sign means a cost increase. A positive sign means a cost saving. It is assumed that the international allowance price would be 17.7 US$/$tCO_2$. Compliance cost and savings are on an annual basis. Original results in € have been converted to US$ at €1 for 1US$.

Source: adapted from Capros and Mantzos (2000, p.8).

Jaccard *et al.* (2002) evaluate the cost of climate policy in Canada. They compare the costs of achieving the Canadian Kyoto target in 2010 (using the CIMS model) for equal sector targets or one national target. According to their estimates, the electricity, residential, and commercial/institutional sectors contribute more, at lower marginal costs, to reductions when there is one national target, while the industry and transportation sectors contribute less. For example, the marginal cost for the electricity sector is about 20 US$/$tCO_2$-eq for the sector target and 80 US$/$tCO_2$-eq for the national target, while those of industrial sector are 200 and 80 US$/$tCO_2$-eq respectively.

Both studies illustrate a general finding that a portfolio of options which attempts to balance emission reductions across sectors with 'equal percentage reductions' is more costly than optimizing the policy mix for cost effectiveness.

Another aspect of mitigation options is the opportunity afforded by portfolio analysis to reduce risks and costs. Because fossil fuel prices are uncertain and variable, there are potential benefits in portfolios of energy supply sources that increase diversity so as to include, in particular, sources such as renewables and nuclear, the costs of which do not depend on fossil fuel prices. Long-standing methods from finance theory can help to quantify a new low-carbon technology's contribution to overall risk, and to quantify costs associated with the development of a set of options for GHG mitigation and energy security. The portfolio approach differs from the traditional stand-alone cost approach in that it introduces market risk and includes inter-relationships between the costs of different technologies (Awerbuch, 2006, MITI). New technologies that diversify the generating mix and low-carbon options tend to be quantifiably more diverse than business-as-usual reliance on fossil fuels (see Stirling, 1994; 1996; Grubb *et al.*, 2006). Moreover, in contrast to the expected year-to-year variability of fossil fuel prices (which can be estimated from historic patterns), operating costs for wind, solar, nuclear and other capital-intensive non-fossil technologies are largely uncorrelated to fossil fuel prices.

Theory, supported by application, suggests that risk-optimized generating mixes will include larger shares of wind, geothermal and other fixed-cost renewables, even where these technologies cost more than gas and coal generation. Optimal mixes will also enhance energy security while simultaneously minimizing expected generating cost and risk. Awerbuch, Stirling, Jansen and Beurskens (2006) explore the limitations of the mean-variance portfolio (MVP) approach, and compare MVP optimal generating mixes to 'maximum diversity' mixes that also provide protection against uncertainty, ignorance and 'surprise'. They find that the optimal mixes in both cases contain larger shares of wind energy.

These findings suggest that portfolios of cross-sector energy options that include low-carbon technologies and products will reduce risks and costs, simply because fossil fuel prices are more volatile relative to other costs, in addition to the usual benefits from diversification.

11.4 Macro-economic effects

The main conclusions from the TAR on the macro-economic costs of mitigation can be summarized as follows. Mitigation costs can be substantially reduced through a portfolio of policy instruments, including those that help to overcome barriers, with emissions trading in particular expected to reduce the costs. However, mitigation costs may be significant for particular sectors and countries over some periods and the costs tend to rise with more stringent levels of atmospheric stabilization. Unplanned and unexpected policies with sudden short-term effects may cost much more for the same eventual results than planned and expected policies with gradual effects. Near-term anticipatory action in mitigation and adaptation would reduce risks and provide benefits because of the inertia in climate, ecological and socio-economic systems. The effectiveness of adaptation and mitigation is increased and costs are reduced if they are integrated with policies for sustainable development.

Since the TAR, the Kyoto Protocol has come into force and there has been a range of domestic initiatives in different countries. This has led to diverse modelling activities addressing the Kyoto Protocol as implemented (without the United States and Australia), post-Kyoto strategies, and more intricate domestic policies, providing more refined estimates of mitigation costs, through more accurate representation of policy implementation, improved modelling techniques, and improved meta-analysis of existing results.

11.4.1 Measures of economic costs

Chapter 2 discusses cost concepts. Here we report, where available, the prices associated with CO_2 emissions, and negative or positive impacts on GDP, welfare and employment.

The TAR reviewed studies of climate policy interactions with the existing tax system. These interactions change the aggregate impact of a climate policy by changing the costs associated with taxes in other markets. They also point to the opportunity for climate policy – through carbon taxes or auctioned permits – to generate government revenue and, in turn, to reduce other taxes and their associated burden. The TAR pointed to this opportunity as a way to reduce climate policy costs. Since the TAR, additional studies have extended the debate (Bach *et al.*, 2002; Roson, 2003). Meanwhile, such arguments have been the basis of the UK Climate Change Levy and linked reduction in National Insurance Contributions, small auctions under the EU ETS and US NO_x Budget Program, large proposed auctions under the Regional Greenhouse Gas Initiative in the United States, and proposals in the United States, Japan, and New Zealand for carbon taxes.

11.4.2 Policy analysis of the effects of the Kyoto Protocol

Most analyses discussed in the TAR focused on national emission policies under the Kyoto Protocol in the form of an economy-wide tax or tradeable permit system. This has continued to be an active area of policy modelling since the Kyoto Protocol came into force. Global cost studies of the Kyoto Protocol since the TAR have considered more detailed implementation questions and their likely impact on overall cost. Chief among these have been the impact of the Bonn-Marrakesh agreements concerning sink budgets, the non-participation of the United States, and banking and the use of 'hot air' (Manne and Richels, 2001; Böhringer, 2002; den Elzen and de Moor, 2002; Löschel and Zhang, 2002; Böhringer and Löschel, 2003; McKibbin and Wilcoxen, 2004; Klepper and Peterson, 2005).

U.S. non-participation in the Kyoto Protocol, coupled with the increase in sink budgets in Bonn and Marrakech, implies that the target for Annex B countries as a whole will likely be met with virtually no effort. In other words, excess allowances in Russian and Ukraine (referred to as 'hot air') roughly equal the shortfall in Europe, Japan, Canada, and other countries. However, some of these same studies emphasize that strategic behaviour by Russia and Ukraine, acting as a supply cartel and/or choosing to bank allowances until the next commitment period, will lead to a positive emission price (Löschel and Zhang, 2002; Böhringer and Löschel, 2003; Maeda, 2003; Klepper and Peterson, 2005). For example, Böhringer and Löschel (2003) use a large-scale static CGE model of the world economy to analyse the costs of Kyoto in different scenarios with and without Annex B emissions trading and U.S. participation. GDP costs of Kyoto for 2010 without US participation, with Annex B trading, but without use of 'hot air' are estimated at 0.03% for Annex B (without US) for a carbon price of 13 US$/$tCO_2$, with a 6.6% reduction in total Annex-B CO_2. Regional GDP costs are 0.05% for the EU15 and Japan, and 0.1% for Canada, with benefits of 0.2% for the European Economies in Transition and 0.4% for Russia and other countries in Eastern Europe, the Caucasus and Central Asia. Without Annex B trading, the costs are estimated at 0.08% for Annex B (without US).

National and regional studies cited below also suggest similar low or negligible costs for the ratified Kyoto Protocol for Canada, the EU and Japan compared with the estimates in the TAR, depending on the extent of trade in emission permits and CDM/JI certificates. The importance of CDM supply and other assumptions on the carbon price is shown in Figure 11.5 (den Elzen and de Moor, 2002).

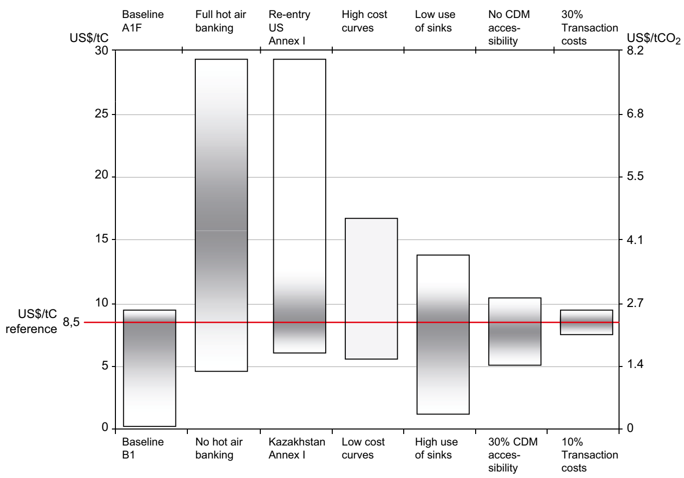

Figure 11.5: *Key sensitivities for the emission permit price from the FAIR model applied to the Kyoto Protocol under the Bonn-Marrakesh Accords*

The following key factors and associated assumptions were chosen for the analysis:

- Baseline emissions: LOW reflects the B1 scenario and HIGH the A1F scenario (IMAGE team, 2001). Our reference is the A1B scenario.
- Hot Air Banking: the LOW case reflects no banking of hot air, with all hot air being banked in the HIGH case; the reference case is one in which hot air banking is optimal for the Annex-I FSU.
- Marginal Abatement Cost (MAC) curves: the MAC curves of WorldScan are used in the reference case while the MAC curves of the POLES model represent the HIGH case.
- Participation Annex I: at the LOW end, we examined the participation of Kazakhstan while the HIGH end reflects US re-entry.
- Sinks: a LOW case has been constructed by assuming that CDM sink credits are capped to 0.5 percent of base year emissions (instead of 1 percent), carbon credits from forest management based on data submitted by the Parties (which are lower than the reported values in Appendix Z, see (Pronk, 2001) and low estimates for carbon credits from agricultural and grassland management using the ALTERRA ACSD model (Nabuurs et al., 2000). The HIGH case reflects sinks credits based on high ACSD estimates for agricultural and grassland management and maximum carbon credits from forest management as reported in Appendix Z. In total, the LOW case implies 70 MtC while the HIGH case implies 195 MtC of carbon credits from sink-related activities. The Marrakesh Accords represent the reference case of 120 MtC.
- CDM Accessibility Factor: this reflects the operational availability of viable CDM projects and is set at 10 percent of the theoretical maximum in the reference case. In the LOW case, we assume no accessibility, while in the HIGH case the factor is set at 30 percent.
- Transaction Costs: the transaction costs associated with the use of the Kyoto Mechanisms are set at 20 percent in the reference case, 10 percent in the LOW case and 30 percent in the HIGH case.

Source: den Elzen and Both (2002, p.43).

11.4.3 National and regional studies of responses to mitigation policies

As individual countries have begun contemplating domestic policy responses (see Chapter 13), an increasing number of studies have focused on more detailed national cost assessments. This increased detail includes both more careful representation of proposed and actual policy responses and more disaggregated results by sector, region, and consumer group. This detail is difficult to achieve in the context of a global model. We briefly summarize the results of studies for various countries/blocks on the basis of the literature available.

11.4.3.1 Policy studies for the United States

Both Fischer and Morgenstern (2006) and Lasky (2003) identify treatment of international trade and the disaggregation of the energy sector as important factors leading to differences in the cost of Kyoto for the US economy. Lasky also identifies energy-demand elasticities and sensitivities to higher inflation as important factors. He concludes that the cost of the US joining Kyoto under Annex I permit trading is between -0.5 to -1.2% of GDP by 2010, with a standardized energy-price sensitivity, and including non-CO_2 gases and sinks, but excluding recycling benefits and any ancillary benefits from improved air quality. The cost falls to 0.2% of GDP with global trading of permits. Barker and Ekins (2004) review the large number of modelling studies dealing with the costs of Kyoto for the US economy that were available when the US administration decided to withdraw from the process. These include the World Resources Institute's meta-analysis (Repetto and Austin, 1997), the EMF-16 studies (Weyant and Hill, 1999) and the US Administration's own study discussed above (EIA, 1998). The review confirms Lasky's range of costs but offsets these with benefits from recycling the revenues from permit auctioning and the environmental benefits of lower air pollution. These co-benefits of mitigation are discussed in Section 11.8 below.

Following U.S. rejection of the Kyoto Protocol, there have been a number of policy proposals in the United States focusing on climate change, most notably two proposed during 2005 Congressional debates over comprehensive energy legislation (the Bingaman and McCain-Lieberman proposals, the Regional Greenhouse Gas Initiative, the Pavley Bill in California, and the earlier proposal by the National Commission on Energy Policy). The costs and other consequences of those proposals are summarized in Table 11.10, as compiled by Morgenstern (2005) from studies by the U.S. Energy Information Administration (1998; 2004; 2005). The sectoral implications of (EIA, 2005) are discussed above in Section 11.3.3.

All estimates derive from EIA's NEMS model, a hybrid top-down, bottom-up model that contains a detailed representation of energy technologies, energy demand, and primary energy supply, coupled with an aggregate model of economic activity (Holte and Kydes, 1997; Kydes, 2000; Gabriel *et al.*, 2001). While the estimates were conducted over a period of seven years, with changes occurring in the baseline, the model produces a remarkably consistent set of estimates, with most physical quantities (including emission reductions) varying more or less linearly with carbon price, and potential absolute GDP impacts varying with the price squared. Real GDP impacts, which include business cycle effects, are less consistent and depend on both policy timing and assumptions about revenue recycling. For example, the real GDP loss of 0.64% shown for 'Kyoto+9%' is reduced to 0.3% by 2020 when recycling benefits are taken into account (EIA, 1998).

Table 11.10: *The EIA's analysis of the Kyoto Protocol, McCain-Lieberman proposal, and Bingman/NCEP proposal: United States in 2020*

	Bingman	McCain-Lieberman	'Kyoto +9%'[a)]
GHG emissions (% domestic reduction compared to baseline)	4.5	17.8	23.9
GHG emissions reductions (million metric tons CO_2 reduced per year in 2010)	404	1346	1690
Allowance price (2000 US$ per ton CO_2)	8	33	40
Coal use (% change from baseline)	-5.7	-37.4	-72.1
Coal use (% change from 2003)	14.5	-23.2	-68.9
Natural gas use (% change from baseline)	0.6	4.6	10.3
Electricity price (% change from baseline)	3.4	19.4	44.6
Potential GDP (% change compared to baseline)[b)]	-0.02	-0.13	-0.36
Real GDP (% change compared to baseline)[b)]	-0.09	-0.22	-0.64

Notes:
a) Kyoto (+9%) refers to a scenario where offsets make up 9% of the U.S. target, thereby allowing domestic emissions to rise 9% above the Kyoto target.
b) GDP in 2020 is estimated to be roughly 20 trillion US$ in 2020, so each 1/100th of a percentage point (0.01%)-equals 2 billion US$. Potential GDP is the level of

Source: Morgenstern (2005).

In addition, EIA (2005) analyses the 2004 scenario of the National Commission on Energy Policy. The estimated cost is 0.4% of the reference case GDP by 2025 and the overall growth of the economy is 'not materially altered' (p. 42). However, no costs were included for the implementation of the 'CAFE' transportation sector portion of the NCEP programme that produced most of the emission reductions.

As an independent, government statistical agency, EIA's modelling results tend to be at the centre of most policy debates in the United States. Researchers at MIT (Paltsev *et al.*, 2003) also provided estimates of impacts associated with the McCain-Lieberman proposal that had similar allowance prices but found roughly one-quarter to one-third of the GDP costs reported in the EIA analyses. This is partly explained by the fact that the EIA uses an econometric model to compute GDP costs derived from historic experience in the face of energy price shocks. The MIT and other CGE models assume that, to a large extent, aggregate costs equal the accumulated marginal costs of abatement, typically yielding lower costs than the econometric models (Repetto and Austin, 1997; EIA, 2003).

A threshold question in the McCain-Lieberman discussion has been whether the exclusion of small sources below 10,000 metric tons (e.g. households and agriculture) would alter the efficiency of the program. Pizer *et al.* (2006) use a CGE model to show that exclusion of these sectors has little impact on costs. However, excluding industry roughly doubles costs while implementing alternative CO_2-reducing policies in the power and transport sectors (a renewable energy standard in the power sector and fuel economy standards for cars) results in costs that are ten times higher.

The states in the U.S. have put forward climate policy proposals. An analysis of a package of eight efficiency measures using a CGE model (Roland-Holst, 2006) indicates that it will reduce GHG emissions by some 30% by 2020 – about half of the Californian target of returning to 1990 CO_2 levels by 2020 – with a net benefit of 2.4% for the state's output and a small increase in employment (Hanemann *et al.*, 2006). These results, driven by bottom-up estimates of potential savings in the vehicle and building efficiency, remain controversial, as the debate over vehicle fuel economy standards demonstrates (see NHTSA, 2006 for a discussion of bottom-up estimates and issues).

11.4.3.2 Policy studies for Canada

Jaccard *et al.* (2003) provide estimates of the costs of reaching the Kyoto targets in Canada as part of their wider effort to reconcile top-down and bottom-up modelling results. Using their benchmark run, and assuming compliance without international trading, they find an allowance price of 100 US$/$tCO_2$-eq with an associated GDP loss of nearly 3% in 2010. They note that, while these costs are in line with similar studies of reduction costs in the United States conducted by EIA, they are considerably higher than alternative results for Canada derived from a bottom-up model, and they predict a roughly 33 US$/$tCO_2$-eq allowance price. The authors then show how, by making what they consider longer-run assumptions – lower capital and greater price sensitivity – they can duplicate the lower GDP costs in their model.

11.4.3.3 Policy studies for Europe

Since the TAR, many studies have analysed the macro-economic costs in Europe of committing to Kyoto or other targets, different trade regimes, and multiple greenhouse gases. We report results from some of the key studies below.

An important development within the European Union has been the production of additional detailed results from individual member states. Viguier *et al.* (2003) provide a comparison of four model estimates of the costs of meeting Kyoto targets without trading (except for the EU estimate) based on the 1998 burden sharing agreement replicated in Table

Table 11.11: *A comparison of estimates of domestic carbon prices, welfare, GDP, and Terms of Trade for domestic emissions trading without international allowance trading (except for the EU total) to achieve the 2010 Kyoto target.*

	Domestic carbon prices (2000 US$/$tCO_2$)				Reduction in consumption (%)	Reduction in GDP (%)	Improvement in Terms of Trade (%)
Model	EPPA	GTEM	POLES	PRIMES	EPPA-EU	EPPA-EU	EPPA-EU
Germany	35.4	52.6	31.8	26.2	0.63	1.17	1.10
France	40.4	-	65.4	42.8	0.67	1.11	1.11
UK	27.1	33.6	39.5	36.6	0.96	1.14	-0.77
Italy	43.7	-	104.6	51.4	1.01	1.47	1.54
Rest of EU	47.6	-	-	65.7	1.23	2.12	1.07
Spain	54.7	-	-	39.8	2.83	4.76	2.06
Finland	64.5	85.9	-	44.6	1.90	2.73	1.67
Netherlands	87.1	-	-	159.3	4.92	7.19	0.55
Sweden	92.2	106.4	-	65.1	3.47	5.11	1.18
Denmark	114.5	118.9	-	56.2	3.97	5.72	-0.74
EU	47.3	46.1	55.9	40.1	Not available	Not available	Not available
USA	68.1	-	52.6	-	0.49	1.01	2.39
Japan	59.8	-	70.8	-	0.22	0.49	2.70

Source: Viguier et al. (2003, p.478)

11.11. EPPA and GTEM are both CGE models, while POLES and PRIMES are partial-equilibrium models with considerable energy sector detail. Viguier *et al.* (2003) explain differences between model results in terms of baseline forecasts and estimates of abatement costs. Germany, for example, has lower baseline emission forecasts in both POLES and PRIMES, but at the same time higher abatement costs. The net effect is that national carbon prices are estimated to be lowest in Germany in POLES and PRIMES while EPPA and GTEM find lower costs in the United Kingdom. Overall, the two general-equilibrium models find similar EU-wide costs located between the POLES and PRIMES estimates.

Viguier *et al.* (2003) go on to discuss the differential consequences across European countries. They find that other measures of cost – welfare and GDP losses – generally follow the pattern of estimated allowances prices, as allowance prices reflect the marginal abatement costs. France, the United Kingdom, and Germany face lower costs and Scandinavian countries generally face higher costs. Terms of trade generally improve for European countries, except for the United Kingdom and Denmark, the former owing to its position as a net exporter of oil and the latter owing to its very low share of fuels and energy-intensive goods in its basket of imports.

There are other studies estimating the equilibrium price in the European market with emissions trading and savings, as compared to a no-trade case (see also 13.2.1.3). An early study by IPTS (2000) calculates the clearing price in the EU market in 2010 at about 50 US$(2000)/$tCO_2$ using the POLES model, with a 25% cost reduction arising from emissions trading among countries, and Germany and the UK emerging as net sellers. A more recent study by Criqui and Kitous (2003), which also uses the POLES model, finds even larger gains and lower prices: the equilibrium allowance price is 26 US$(2000)/$tCO_2$[10], and trading among countries reduces total compliance costs by almost 60%. Without any competition from non-trading European countries and the other Annex B countries on the JI and CDM credits market, they further estimate that the allowance price collapses from 26 US$/$tCO_2$ to less than 5 US$/$tCO_2$, and the annual compliance costs are reduced by another 60%. Using the PRIMES model, Svendsen and Vesterdal (2003) find reductions in costs of 13% from trading within the electricity sector in the EU, 32% EU economy-wide trading, and 40% from Annex B trading. Klepper and Peterson (2004; 2006) consider the division between trading and non-trading sectors in the EU, and emphasize the potential inefficiency of generous allocation plans if the non-trading sectors are forced to make up the difference without significant use of the Kyoto mechanisms.

Eyckmans *et al.* (2000) investigate the EU Burden Sharing Agreement on the distribution of the Kyoto emissions reduction target over the EU member states, without the EUETS. Even

10 Prices in euros in the citation have been converted at 2000 average rates of $1 to 1 euro.

if only cost efficiency is taken into account, they argue that the burden sharing agreement does not go far enough towards equalizing marginal abatement costs among the member states. For instance, some poorer EU member states have been allowed to increase their emissions considerably, but still their allowances are too low. Introducing a measure of inequality aversion reinforces most of the conclusions.

Other studies have looked at the savings from a multigas approach in Europe. The European Commission (1999) finds that, at a cost below about 50 US\$/CO_2-eq, 42% of total reduction needed may come from non-CO_2 emissions. Burniaux (2000) finds that a multigas approach reduces the costs of implementing the Kyoto Protocol in the European Union by about one third. For Eastern European countries, the reduction in costs will be even higher when they use a multigas approach. Jensen and Thelle (2001) find similar results using the EDGE model to include non-CO_2 gases, with EU welfare costs falling from about 0.09% to 0.06% in 2010 compared to the baseline.

Babiker *et al.* (2003) use the EPPA-EU model to study the idea that emission permits trade may negatively impact welfare in some cases because of the presence of non-optimal taxation in the pre-trade situation. The selling of permits pushes up a country's carbon price. When a rise in price comes on top of an already distorted fuel price, this results in an additional negative effect on welfare, which might outweigh the gains from sales of permits. It is a negative price effect and a positive income effect. This study finds that some countries, like Scandinavian countries or Spain (mainly importers of carbon permits), would be better off with international trading. Others, like the United Kingdom, Germany or France (mainly exporters of permits) are worse off with trading than without.

In summary, the costs of committing to the Kyoto Protocol may be less than 0.1% of GDP in Europe with flexible trading. U.S. rejection of the Kyoto Protocol reduces the costs of Kyoto in Europe if there are flexible mechanisms in place but, because of the effects of trading terms, pushes costs upwards in the absence of emissions trading or other flexible mechanisms. The permit prices and costs depend on restrictions on trade and the possible exercise of market power in the emission permit market. Multiple greenhouse gas abatement will reduce costs compared to a situation with only CO_2 abatement, a point also emphasized in Section 3.3.5.4.

11.4.3.4 Policy studies for Japan

Masui *et al.* (2005) examine the effects of a carbon tax in Japan to meet the Kyoto target using the AIM (Asia-Pacific Integrated Model). By 2010, a carbon tax with lump-sum recycling leads to an average GDP loss of 0.16% and a tax of 115 US\$/tCO_2. A tax and subsidy regime with carbon tax revenue used to subsidize CO_2 reduction investments leads to an average GDP loss of 0.03% and a tax of 9 US\$/tCO_2. By contrast, Hunt and Ninomiya (2005) look at emission trends and argue that as long as growth is less than 1% per year, and the carbon intensity of energy does not rise, Japan should be able to achieve its target, for example through the Kyoto Target Achievement Plan. If growth is closer to 2% per year, the plan will not suffice.

11.4.3.5 Policy studies for China

The ERI (2003) report on three alternatives for China's development to 2020 presents effects of policies that reduce CO_2 emissions in a 'green growth' scenario. For the same GDP growth of 7% per year, policies of accelerated economic reform, increased energy efficiency standards, higher taxes on vehicle fuels and more use of low-carbon technologies in power generation reduce the growth of CO_2 to 1.7% per year compared to 3.6% per year in an 'ordinary effort' scenario.

Chen (2005) presents a comparison of assumed marginal abatement cost curves and GDP costs associated with various reduction efforts in China in different models (see Figure 11.6 and Table 11.12 below). Chen (p. 891) discusses the reasons for the differences, which are largely due to differences in baselines and assumptions about available technologies and substitution between fossil and non-fossil energy. GDP costs for 2010 vary: 0.2 and 1.5% reduction compared to baseline, associated with a 20% reduction in CO_2 compared to baseline. Garbaccio *et al.* (1999) consider smaller CO_2 reductions – between 5 and 15% – and find not only lower costs, but potentially positive GDP effects after only a few years owing to a double-dividend effect.

11.4.4 Post-Kyoto studies

The macro-economic cost measure adopted in the literature on mitigation costs is generally GDP or gross marketed world output, excluding valuations of environmental costs and benefits.

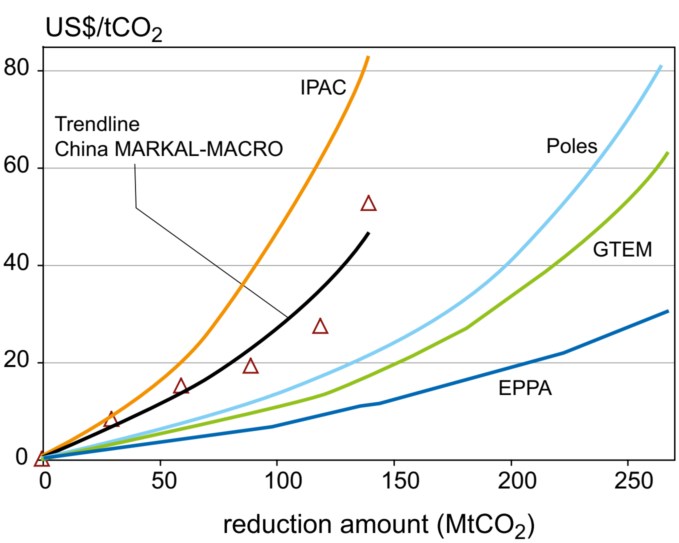

Figure 11.6: *A comparison of Marginal Abatement Curves for China in 2010 from different models*

Source: adapted from Chen (2005, p. 891)

Table 11.12: *A comparison of GDP loss rates for China across models in 2010*

Model	Emission reduction compared to baseline (%)	Marginal carbon abatement cost ((2000)US$/t$CO_2$)	GDP (GNP) loss relative to baseline (%)
GLOBAL 2100	20 30	25 50	1.0 1.9
GREEN	20 30	4 7	0.3 0.5
Zhang's CGE model	20 30	7 13	1.5 2.8
China MARKAL-MACRO	20 30 40	18 22 35	0.7 1.0 1.7

Notes: Marginal carbon abatement costs were originally measured at 1990 prices in GLOBAL 2100, at 1985 prices in GREEN, at 1987 prices in Zhang's CGE model, and at 1995 prices in China MARKAL-MACRO. They were converted to 2000 prices for comparison with other carbon prices in the chapter.

Source: adapted from Chen (2005, p.894)

11.4.4.1 A comparison of the macro-economic costs of mitigation to 2030 from modelling studies

Since the TAR, groups of modellers have found a reduction in expected macro-economic costs as a result of the use of multigas options (EMF21, Weyant *et al.*, 2006) (see Section 3.3.5.4) and because carbon prices affect technological change in the models (EMF19, IMCP) (see Section 11.5). Figure 11.7 summarizes the 2030 data brought together in these studies as well in as other post-TAR Category III (stabilization at around 550ppm CO_2-eq) studies covered in Chapter 3.[11] The figure is in 3 parts, showing (a) the carbon prices in US$(2000) by 2030 (typically a rising trend) and their effects on CO_2 emissions, (b) the effects of CO_2 abatement on GDP, and (c) the relationship between carbon prices and gross world output (GDP). All data are differences from the baseline projections for 2030. The studies are grouped around two of the stabilization categories set out in Chapter 3 (Table 3.5), with corresponding insights.

Category IV stabilization trajectories from 25 scenarios: In most models (24 of the 25 scenarios[12]) the 'optimal' trajectory towards stabilization at 4.5W/m^2 (EMF21 studies), or the near-equivalent 550 ppm CO_2-only (IMCP and EMF19), requires abatement at less than 20% CO_2 compared to baseline by 2030, with correspondingly low-carbon prices (mostly below 20 US$/t$CO_2$-eq, all prices in 2000 US$). Costs are less than 0.7% global GDP, consistent with the median of 0.2% and the 10–90 percentile range –0.6 to 1.2% for the full set of scenarios given in Chapter 3 (see Figure 3.14). Carbon prices in the EMF21 multigas studies for 4.5W/m^2 by 2030 average 18 US$/t$CO_2$-eq, and span 1.2–26 US$/tCO_2-eq, except one at 110 US$/t$CO_2$-eq. Carbon prices in the corresponding 550 ppm CO_2-only studies in EMF19 average 14 US$/t$CO_2$ and span 3-19 US$/ t$CO_2$-eq, except one at 50 US$/tCO_2. Six of the IMCP 550 ppm CO_2-only models have 2030 prices in the range 7–12 US$/t$CO_2$, but four have low to zero prices in 2030, bringing the average to only 6 US$/t$CO_2$.

Category III stabilization trajectories from 12 scenarios: In 11 of the 12 post-TAR scenarios,[13] abatement is less than 40% of CO_2 by 2030. Costs are below 1% GDP, consistent with the median of 0.6% and the 10–90 percentile range 0 to 2.5% for the full set in Chapter 3, which also has a range of 18–79 US$/t$CO_2$-eq for carbon prices (see Figure 3.14). The largest comparable dataset available in this category is the IMCP 450ppm CO_2-only studies. Most of these produce a carbon price by 2030 in the range 20–45 US$/t$CO_2$, with one higher outlier, and a mean of 31 US$/t$CO_2$ (just over 110 US$/tC). The other Category III models nearly all give higher prices.

The lower estimates of costs and carbon prices for studies assessed here, in comparison with the full set of studies reported in Chapter 3, are mainly caused by a larger share of studies that allow for enhanced technological innovation triggered by climate policies; see 11.5 below. The impact of endogenous technological change is greater for more stringent mitigation scenarios.

Figures 11.7 (a) and (c) show how the carbon prices affect CO_2 and global GDP in the models. Note that carbon prices are rising (not shown in Figure 11.7) – sharply for some of the higher numbers – from lower levels in 2020 and also

11 These include three scenarios in the U.S. Climate Change Science Program (US CCSP, 2006). Note that the cost assessment presented here is based on a smaller set of scenarios than the assessment in Chapter 3. While Chapter 3 uses the full set of scenarios, including the post-SRES of the TAR, the assessment here relies on post-TAR studies that report information for macro-economic costs. In other words, modelling studies that do not give integrated GDP results are excluded from Figure 11.7 and the associated discussion in this chapter. While Chapter 3 focuses primarily on the assessment of representative cost ranges covering a larger sample, this chapter focuses on the comparative analysis of different post-TAR studies exploring the relationship between the cost indicators and their determinants in the models.

12 The excluded scenario is also an outlier in that FUND is the only EMF21 model to show a declining path for carbon prices, which fall to near zero by 2100 (Weyant *et al*, 2006, p. 25).

13 These scenarios exclude post-SRES results, which did not report carbon prices; see footnote 11. The Category III outlier scenario comes from the CCSP-IGSM model. The price rises to 1651 US$/tCO2 by 2100. This high price is partly due to the assumption of the limited substitution of fossil fuels by electricity as an energy source for transportation: 'In the IGSM scenarios, fuel demand for transportation, where electricity is not an option and for which biofuels supply is insufficient, continues to be a substantial source of emissions.' (US CCSP, 2006, p. 4–21).

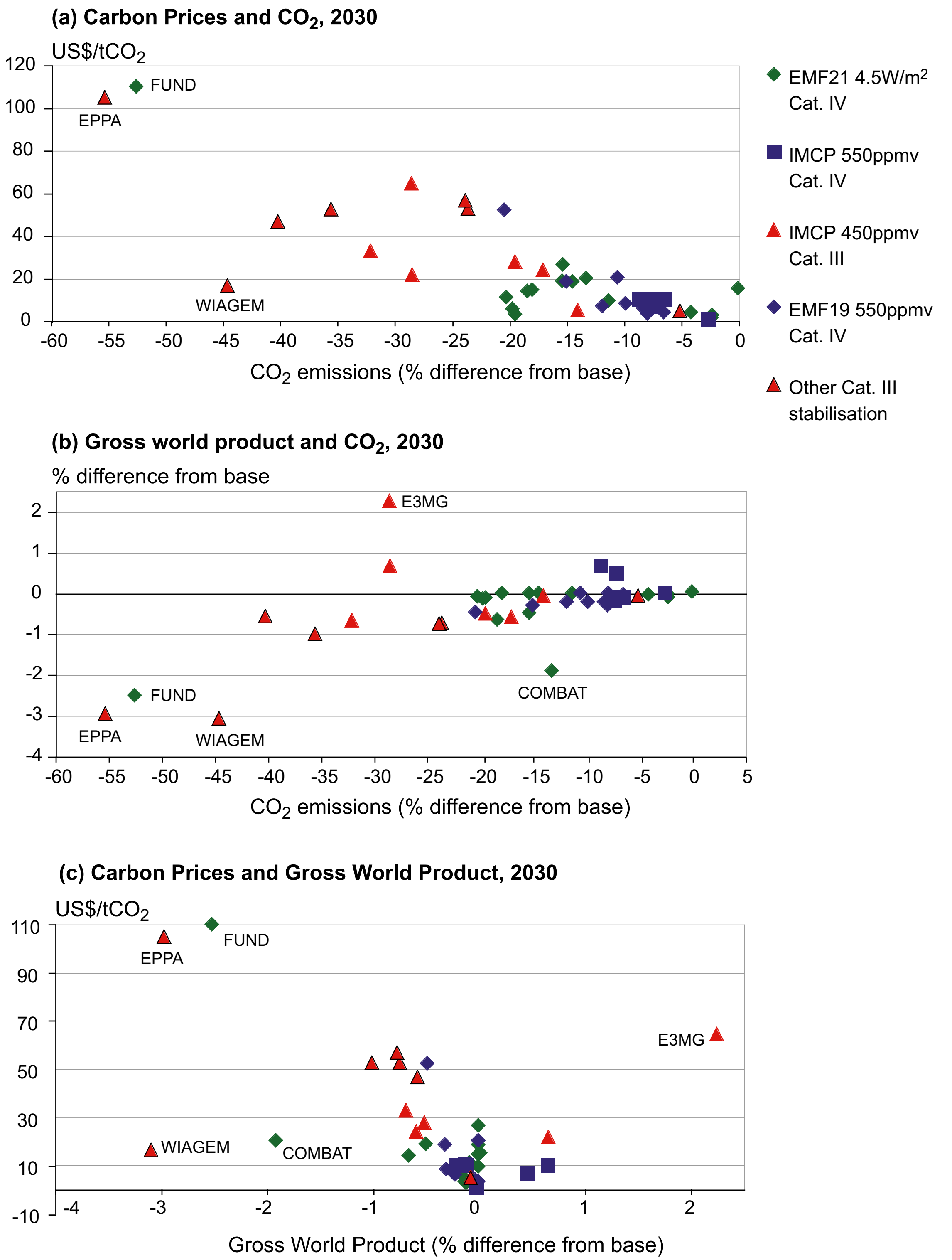

Figure 11.7: *Year 2030 estimated carbon prices and gross-world-product (GDP) costs of various pathways to stabilization targets*

Notes: Figure 11.7 shows, for 2030, the carbon price, CO_2 abatement relative to the baseline, and global GDP differences from baseline for five different sets of stabilization studies: EMF21 radiative forcing at 4.5 W/m^2 (multigas); IMCP at 550 and 450ppm (CO_2-only with induced technological change); EMF19 at 550ppm (CO_2-only with induced technological change) and 6 studies in category III included in Figure 3.24. The results as shown exclude incomplete sets (i.e. data have to be available for all three variables shown). The EMF21 results exclude studies unsuitable for near-term analysis (e.g. substantial effects for a past year). The IMCP results exclude those from two experimental/partial studies. The breakdown into Category III and IV scenarios treats CO_2-only studies as if they also allow for cost-effective non-CO_2 multigas GHG mitigation (see Table 3.14). Note that prices and outputs are based on various definitions, so the figures are indicative only. The price bases in the original studies vary and have been converted to 2000 US$.

Sources: Weyant, 2004; Masui et al., 2005; Edenhofer et al., 2006b, Weyant et al., 2006 and Chapter 3.

after 2030. Most models considered in this analysis therefore suggest that the 20–50 US$/t$CO_2$ cost category of the sector studies is the carbon price level which, if reached globally by 2020–2030, delivers trajectories compatible with subsequent stabilization at mid-category III levels. The corresponding CO_2 reduction by 2030 is 5–40% relative to baseline (which varies between studies, with higher baselines giving higher reduction percentages in 2030).

Figure 11.7 (b) shows the CO_2 abatement plotted against world GDP. In most studies, higher abatement is associated with higher loss of GDP. The relationships vary, and two models in particular stand out as radically different from others (E3MG and FUND). Three models in the IMCP predict GDP gains under different assumptions.[14] These prices and costs are largely determined by the approaches and assumptions adopted by the modellers, with GDP outcomes being strongly affected by assumptions about technology costs and change processes (see 11.5 below), the use of revenues from permits and taxes (see above), and capital stock and inertia (considered in 11.6) (Barker *et al.*, 2006a; Fischer and Morgenstern, 2006).

11.4.4.2 Other modelling studies

Bollen *et al. (2004)*, using Worldscan (a global CGE model), consider the consequences of post-Kyoto policies seeking a 30% reduction for Annex B countries below 1990 levels by 2020. They do not include the CDM, sinks or induced technological change in the modelling. Like most studies, they find dramatically lower costs when global trading occurs. With only Annex I countries participating in emissions trading, the high-growth benchmark case shows an allowance price of about 130 US$(2000)/t$CO_2$, and a 2.2% reduction below baseline for Annex I GDP. With global trading, the allowance price is about 17 US$(2000)/t$CO_2$ and there is a much lower loss of 0.6% in GDP. In a more modest scenario that focuses exclusively on maintaining the current Kyoto targets for all Annex B countries, Russ, Ciscar, and Szabo (2005) estimate a 7 US$(2000)/t$CO_2$ price and a 0.02–0.05% GDP loss in 2025 with global trading (using the POLES and GEM-E3 models).

A number of other studies consider post-Kyoto impact out to 2025 or 2050 based on approaches to stabilization, typically at 550 ppm CO_2-eq (category III of Table 3.10) (longer-term strategies are discussed in Chapter 3; discussions of policy mechanisms are covered in Chapter 13). For example, Den Elzen *et al.* (2005), using the IMAGE-FAIR modelling system, show that different assumptions about business-as-usual emission levels and abatement cost curves lead to a range of marginal costs of between 50 US$ and 200 US$/t$CO_2$-eq and of total direct abatement costs of between 0.4 and 1.4% of world GDP in 2050, consistent with a recent EU report (EEA, 2006).

The Stern Review (2006), which was commissioned by the UK Treasury, also considers a range of modelling results. Drawing on estimates from two studies, it reports the costs of an emissions trajectory leading to stabilization at around 500–550ppm CO_2-eq. One of the two studies (Anderson, 2006) calculates estimates of annual abatement costs (i.e. not the macro-economic costs) of 0.3% of GDP for 2015, 0.7% for 2025 and 1% for 2050 from an engineering analysis based on several underlying reports of future technology costs. His uncertainty analysis, exploring baseline uncertainties about technology costs and fuel prices, shows a 95% prediction range of costs from –0.5% to +4% of GDP for 2050. The other study is a meta-analysis by Barker et al. (2006a) and looks at the macro-economic costs in terms of GDP effects. The study aims to explain the different estimates of costs for given reductions in global CO_2 in terms of the model characteristics and policy assumptions adopted in the studies. With favourable assumptions about international flexibility mechanisms, the responsiveness and cost of low-carbon technological change, and tax reform recycling revenues to reduce burdensome taxes, costs are lowered, and in some cases become negative (i.e. GDP is higher than baseline).

In summary, various post-2012 Kyoto studies have been completed since the TAR. Nearly all those focusing on 550 and 650 ppm CO_2-eq stabilization targets (Categories B and C, Table 3.10) with a 5–40% reduction in global CO_2 below baseline by 2030, find total costs of about 1% or lower of global GDP by 2030. The critical assumption in these studies is global emissions trading, but there is limited consideration of multi-gas stabilization and endogenous technological change across the studies, and no co-benefits. The few studies with baselines that require higher CO_2 reductions to achieve the targets require higher carbon prices and report higher GDP costs. As noted in Sections 11.5 (induced technological change), 3.3.5.4 (multi-gas approaches), and 11.8.1 (co-benefits), these considerations all tend to lower costs or provide non-climate benefits, perhaps substantially.

11.4.5 Differences between models

Research has continued to focus on differences in various cost estimates between models (Weyant, 2000; Weyant, 2001; Lasky, 2003; Weyant, 2003; Barker *et al.*, 2006a; Fischer and Morgenstern, 2006). Weyant (2001) argues that the five major determinants of costs are: projections for base case GHG emissions; climate policy (flexibility, for example); substitution possibilities for producers and consumers; the rate and process of technological change; and the characterization of mitigation benefits. Turning to the base case, he notes the importance of assumptions about population and economic activity, resource availability and prices, and technology availability and costs.

14 E3MG (Barker et al., 2006b) takes a Post Keynesian approach, allowing under-used resources in the global economy to be taken up for the extra low-carbon investment induced by climate policies when permit/tax revenues are recycled by reducing indirect taxes. Such a response to revenue recyling is a feature of regional studies reported in the TAR (p. 518). FEEM-RICE (Bosetti et al., 2006) allows international cooperation in climate policies to increase the productivity of R&D investment. ENTICE-BR (Popp, 2006a), in a scenario which assumes a high elasticity of substitution between backstop and fossil fuels, shows increasing global output above baseline with more stringent stabilization targets (p. 173).

The key policy feature is flexibility, in other words whether trading over companies, nations, gases, and time is allowed. Substitution possibilities are governed by assumptions about the malleability of capital, economic foresight, and technology detail. Technology modelling includes assumptions about whether technological change is endogenous or exogenous, and whether technology costs drop with increasing use of technologies. Finally, mitigation benefits may be included in varying degrees in different models.

The factors accounting for differences between cost estimates can be divided into three groups: features inherent in the economies being studied (for example, high substitution possibilities at low cost), assumptions about policy (such as the use of international trading in emission permits, or the recycling of auction revenues), and simplifying assumptions chosen by the model builders to represent the economy (how many sector or regions are included in the model). The first two sets of factors can be controlled by specifying the countries and time-scales of the mitigation action, and the exact details of the policies, as in the EMF-16 studies. However, differences in modellers' approaches and assumptions persist in the treatment of substitution and technology. The various factors can be disentangled by a meta-analysis of published finding (this may include an analysis of analyses). This technique was first used in this context by Repetto and Austin (1997) in a mitigation-cost analysis of GDP costs for the US economy. Fischer and Morgenstern (2006) conduct a similar meta-analysis dealing with the carbon prices (taken to be the marginal abatement costs) of achieving Kyoto targets reported by the EMF-16 studies and discussed in the TAR (Weyant and Hill, 1999).

The crucial finding of these meta-analyses is that most of the differences between models are accounted for by the modellers' assumptions. For example, the strongest factor leading to lower carbon prices is the assumption of high substitutability between internationally-traded products. Other factors leading to lower prices include the greater disaggregation of product and regional markets. This suggests that any particular set of results about costs may well be the outcome of the particular assumptions and characterization of the problem chosen by the model builder, and these results may not be replicated by others choosing different assumptions.

Like earlier studies, the comparison of model results in Barker *et al.,* (2006a) emphasizes that the uncertainty in costs estimates comes from both policy and modelling approaches as well as the baseline adopted. Uncertainty about policy is associated with the design of the abatement policies and measures (flexibility over countries, greenhouse gases and time) and with the use of carbon taxes or auctioned CO_2 permits to provide the opportunity for beneficial reforms of the tax system or incentives for low-carbon innovation. In addition, targeted reductions in fossil-fuel use resulting from climate policies can yield benefits in terms of non-climate policy e.g. reductions in local air pollution. Uncertainty about the modelling approaches is associated with the extent to which substitution is allowed in terms of backstop technology, whether the economy responds efficiently (in terms of the use of CGE models), and whether technological change is assumed to respond to carbon prices, the topic of the next section. Uncertainty about the baseline is associated with assumptions adopted for rates of technological change and economic growth, and future prices of fossil fuels.

11.5 Technology and the costs of mitigation

11.5.1 Endogenous and exogenous technological development and diffusion

A major development since the TAR has been the treatment of technological change in many models as endogenous – and therefore potentially induced by climate policy – compared to previous assumptions of exogenous technological change that is unaffected by climate policies (see glossary for definitions). This section discusses the effect of the new endogenous approach on emission permit prices, carbon tax rates, GDP and/or economic welfare, and policy modelling (Chapter 2, Section 2.7.1 discusses the concepts and definitions, and Chapter 13 provides a broader discussion of mitigation and technology policy choices).

The TAR reported that most models make exogenous assumptions about technological change (9.4.2.3) and that there continues to be active debate about whether the rate of aggregate technological change will respond to climate policies (7.3.4.1). The TAR also reported that endogenizing technological change could shift the optimal timing of mitigation forward or backward (8.4.5). The direction depends on whether technological change is driven by R&D investments (suggesting less mitigation now and more mitigation later, when costs decline) or by accumulation of experience induced by the policies (suggesting an acceleration in mitigation to gain that experience, and lower costs, earlier). Overall, the TAR noted that differences in exogenous technology assumptions were a central determinate of differences in estimated mitigation costs and other impacts.

Table 11.13 lists the implications for modelling of exogenous and endogenous technological change[15] and demonstrates the challenges for research. The table shows that, at least in their simplified forms, the two types of innovation processes potentially have very different policy implications in a number of different dimensions.

15 See 'technological change' in the Glossary.

Table 11.13: *Implications of modelling exogenous and endogenous technological change*

	Exogenous technological change	Endogenous technological change
Process	Technological change depends on autonomous trends	Technological change develops based on behavioural responses, particularly (a) choices about R&D investments that lower future costs; and (b) levels of current technology use that lower future technology cost via learning-by-doing
Modelling implications		
Modelling term	Exogenous	Endogenous / induced
Typical main parameters	Autonomous Energy Efficiency Index (AEEI)	Spillovers to learning / return to R&D / cost of R&D / Learning rate
Optimization implications (note: not all modelling exercises are dynamically optimized)	Single optimum with standard techniques	Potential for multiple-equilibria; unclear whether identified solutions are local or global optima
Economic/policy implications		
Implications for long-run economics of climate change	Atmospheric stabilization below approximately 550 ppm CO_2 likely to be very costly without explicit assumption of change in autonomous technology trends.	Stringent atmospheric stabilization may or may not be very costly, depending on implicit assumptions about responsiveness of endogenous technological trends.
Policy instruments that can be modelled	Taxes and tradable permits	Taxes and tradable permits as well as R&D and investment incentives / subsidies
Timing implications for mitigation and mitigation costs associated with cost minimization	Arbitrage conditions suggest that the social unit cost of carbon should rise over time roughly at the rate of interest.	Learning-by-doing implies that larger (and more costly) efforts are justified earlier as a way to lower future costs.
'First mover' economics	Costs with few benefits	Potential benefits of technological leadership, depending on assumed appropriability of knowledge
International spillover / leakage implications	Spillovers generally negative (abatement in one region leads to industrial migration that increases emissions elsewhere)	In addition to negative spillovers from emission leakage / industrial migration, there are also positive spillovers (international diffusion of cleaner technologies induced by abatement help to reduce emissions in other regions)

The role of technology assumptions in models continues to be viewed as a critical determinant of GDP and welfare costs, and emission permit prices or carbon tax rates (Barker *et al.*, 2002; Fischer and Morgenstern, 2006). These analyses cover large numbers of modelling studies undertaken before 2000 and regard the treatment of technology as influential in reducing costs and carbon prices, but find that the cross-model results on the issue are conflicting, uncertain and weak. Since the TAR, there has been considerable focus on the role of technology, especially in top-down and hybrid modelling, in estimating the impact of mitigation policies. However, syntheses of this work tend to reveal wide differences in the theoretical approaches, and results that are strongly dependent on a wide range of assumptions adopted (Barker *et al.*, 2006a; Stern, 2006), about which there is little agreement (DeCanio, 2003).

The approaches to modelling technological change (see Section 2.7.2.1), include (1) explicit investment in research and development (R&D) that increases the stock of knowledge, (2) the (typically) cost-free accumulation of applying that knowledge through 'learning-by-doing' (LBD); and (3) spillover effects. These approaches are in addition to simple analyses of sensitivity to cost assumptions, especially when technological change is treated as exogenous. There have been many reviews (see Clarke and Weyant, 2002; Grubb *et al.*, 2002b; Löschel, 2002; Jaffe *et al.*, 2003; Goulder, 2004; Weyant, 2004; Smulders, 2005; Grübler *et al.* 2002; Vollebergh and Kemfert, 2005; Clarke *et al.*, 2006; Edenhofer *et al.*, 2006b; Köhler *et al.*, 2006; Newell *et al.*, 2006; Popp, 2006b; Sue Wing, 2006; Sue Wing and Popp, 2006). One feature that emerges from the studies is the considerable variety in the treatment of technological change and its relationship to economic growth. Another is the substantial reductions in costs apparent in some studies when endogenous technological change is introduced, comparable to previously estimated cost savings from *ad hoc* increases in the exogenous rate of technological change (Kopp, 2001) or in the modelling of advanced technologies (Placet *et al.*, 2004 p. 5.2 & 8.10).

This section reviews the effect of endogenizing technological change on model estimates of the costs of mitigation. It follows the majority of the literature and takes a cost-effectiveness approach to assess the costs associated with particular emission or cumulative emission goals, such as post-2012 CO_2 reduction below 1990 levels or medium-term pathways to stabilization.

Table 11.14: *Technology policies and modelling approaches*

Policies	Modelling approach	Key points for measuring costs
R&D in low-GHG products and processes from: • Corporate tax incentives for R&D (supply-push R&D) • More government-funded R&D (supply-push R&D)	• Explicit modelling of R&D stock(s) that are choice variables, like capital, and enter the production function for various (low-carbon) goods. • R&D policies can be modelled as explicit increases in R&D supply or subsidies for the R&D price.	The assumed rate of return from R&D, typically based on an assumption that there are substantial spillovers and that the rate of return to R&D is several times higher than conventional investment at the margin due to spillover. Another important point is the assumed cost of R&D input, which may be high if it is taken from other R&D (crowding-out)
Learning-by-doing: • Purchase requirements or subsidies for new, low-GHG products • Corporate tax incentives for investment in low-GHG products and processes	More production from a given technology lowers costs.	Rate at which increases in output lowers costs and long-run potential for costs to fall.

The review shows that endogenizing technological change – via R&D responses and learning-by-doing – lowers costs, perhaps substantially, relative to estimates where the path of technological change is fixed from the baseline. The degree to which costs are reduced hinges critically on assumptions about the returns from climate change R&D, spillovers (across sectors and regions) associated with climate change R&D, crowding-out associated with climate change R&D, and (in models with learning-by-doing) assumed learning rates. Table 11.14 shows the policies that have been modelled to induce technological change, and how they have been introduced into the models.

The policies are in two groups: effects through R&D expenditure, and those through learning-by-doing.Unfortunately, our empirical understanding of these phenomena over long periods of time is no better than our ability to forecast exogenous rates of change. As Popp (2006b) notes, none of the ETC models he reviews use empirical estimates of technological change to calibrate the models because, until recently, there were few empirical studies of innovation and environmental policy. So although we are confident that mitigation costs will be lower than those predicted by models assuming historically-based, exogenous rates of technological change, views continue to differ about how much lower they will be.

11.5.2 Effects of modelling sectoral technologies on estimated mitigation costs

The Energy Modelling Forum conducted a comparative study (EMF19) with the aim of determining how models for global climate change policy analyses represent current and potential future energy technologies, and technological change. The study assesses how assumptions about technology development – whether endogenous or exogenous – might affect estimates of aggregate costs for a 550 ppm CO_2 concentration stabilization target. The modellers emphasize the detailed representations for one or more technologies within integrated frameworks. Weyant (2004) summarizes the results, which indicate low GDP costs and a wide range of estimated carbon tax rates hinging on assumptions about baseline emission growth, as well as technology developments with regard to carbon capture, nuclear, renewables, and end-use efficiency. Figure 11.8 shows that the carbon tax rates are very low before 2050, with all models indicating values below about 14 US$/t$CO_2$ to 2030. Six of the nine models generate values below 27 US$/t$CO_2$ by 2050. By comparison, the EU ETS price of carbon reached nearly 35 US$/t$CO_2$ in August 2005 and again in April 2006.

Perhaps more revealing in the EMF-19 study are the specific features chosen by various modelling teams in their respective papers. Six teams focused on carbon capture and storage (Edmonds *et al.*, 2004; Kurosawa, 2004; McFarland *et al.*, 2004; Riahi *et al.*, 2004; Sands, 2004; Smekens-Ramirez Morales, 2004), one on nuclear (Mori and Saito, 2004), one on renewables (van Vuuren *et al.*, 2004), two on end-use efficiency (Akimoto *et al.*, 2004; Hanson and Laitner, 2004), and one on an unspecified carbon-free technology (Manne and Richels, 2004).

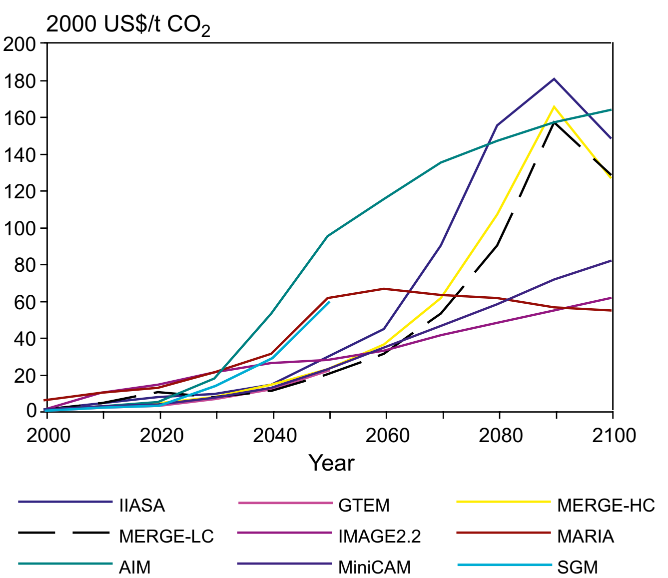

Figure 11.8: *Carbon price projections for the 550 ppm CO_2-only stabilization scenario*

Source: Weyant (2004).

The impacts associated with varying technology assumptions within a given model ranged from a net economic gain, to substantial cuts in the cost of stabilization, to almost no effect on the cost of stabilization.

Despite the wide range of results, they suggest some overarching conclusions (Weyant, 2004). First, technological development, however and under whatever policy it unfolds, is a (if not *the*) critical factor determining the long-term costs and benefits of mitigation. Second, there is no obvious silver bullet: a variety of technologies may be important depending on local circumstances in the future, and a portfolio of investments will be necessary to achieve significant mitigation at lower costs. Third, major technology shifts like carbon capture, advanced nuclear, and hydrogen require a long transition as learning-by-doing accumulates and markets expand so that they tend to play a more significant role in the second half of the century. By contrast, end-use efficiency may provide major opportunities in the shorter term.

11.5.3 The costs of mitigation with and without endogenous technological change

Modellers have pursued two broad approaches to endogenizing technological change, usually independently of each other: explicit modelling of R&D activities that contribute to a knowledge stock and reduce costs, and the accumulation of knowledge through learning-by-doing. Sijm (2004) and Edenhofer *et al.* (2006b) provide detailed comparative assessments of different implementations of both approaches with a focus on mitigation costs when endogenous technology effects are 'switched on'. Their syntheses provide a useful window for understanding the variation in results and how policies might induce technological change.

In his review, Sijm (2004) distinguishes top-down models that mostly focus on explicit R&D effects, and bottom-up models that focus mostly on LBD effects. Among the top-down models, which are described in Table 11.15, he finds considerable variation in the effect of including Endogenous Technological Change (ETC). While some models find a large reduction in mitigation costs (e.g. Popp, 2006a), some find small impacts (e.g. Nordhaus, 2002). These differences can be attributed to:

- the extent of substitution allowed of low-carbon fuels for high-carbon fuels. When this factor is included, the reduction in costs is more pronounced, and the higher it is, the greater the reduction.
- the degree of 'crowding-out' associated with energy R&D expenditures. If new energy R&D is assumed to be in addition to existing R&D, this will generate larger reductions in mitigation than if new energy R&D is assumed to lead to a reduction in R&D elsewhere.
- the approach to spillover. In addition to justifying higher rates of return from R&D, spillover implies that the market outcome with too little investment could be improved by policy intervention.
- the degree of differentiation among R&D activities, the assumed rates of return from those activities, and the capacity of R&D activities to lower costs for low-carbon technologies.
- the rate of learning if LBD is included. Higher rates imply larger reductions in mitigation costs with ETC included.

The first point is that the way low-carbon and high-carbon energy are treated in the models –whether as complements or substitutes – is critical is determining the flexibility of the model to low-carbon innovation and costs of mitigation. Models that do not allow high levels of substitution between low-carbon and high-carbon energy (Goulder and Mathai, 2000; Nordhaus, 2002; Popp, 2006b) indicate that R&D has less impact than those that do, e.g. by introducing a carbon-free backstop technology (Gerlagh and Lise, 2005; Popp, 2006b). Similar results are found more widely for LBD and R&D models: the more substitution possibilities allowed in the models, the lower the costs (Edenhofer *et al.*, 2006a, p.104).

When providing evidence to support the second point – the studies of induced R&D effects via the stock of knowledge – Goulder and Schneider (1999), Goulder and Mathai (2000), Nordhaus (2002), Buonanno *et al.* (2003) and Popp (2004) differ considerably about the extent of crowding-out. In other words, does R&D have an above-average rate of return and does an increase in R&D to support the carbon-saving technologies come from ordinary production activities (no crowding-out), or equally valuable R&D in other areas (crowding-out)? Nordhaus (2002) assumes complete crowding-out in which carbon-saving R&D has a social rate of return that is four times the private rate of return but, because it is assumed that it replaces other equally valuable R&D activities, it costs four times as much as conventional investment. At the other extreme, Buonanno *et al.* (2003) consider spillovers that lead to similarly high social rates of return, but without the higher opportunity costs. Not surprisingly, Nordhaus finds very modest mitigation cost savings and Buonanno *et al.* find enormous savings. In general, induced technological change in a general-equilibrium framework has its own opportunity costs, which may reduce the potential for cost reduction in CGE models substantially.

Popp (2006b), in turn, suggests on the basis of the empirical evidence that half of the R&D spending on energy in the 1970s and 1980s took place at the expense of other R&D. Something between full and partial crowding-out appears more recently in Gerlagh and Lise (2005). Goulder and Matthai (2000) provide an example of the importance for cost reduction of parameters describing returns from R&D and capacity for innovation. They compare both R&D as new knowledge and learning-by-doing (LBD), finding a 29% reduction in the marginal costs with R&D by 2050 and 39% with LBD. As they note, however, this reflects the calibration of their model to a 30% cost saving based on Manne and Richels' assumptions (1992). The model results simply reflect the choice of calibrated parameter values.

Table 11.15: *Treatment of endogenous technological change (ETC) in some global top-down integrated assessment models*

Study	Model	ETC channel	Number of production sectors	Number of regions	Major results (impact of ETC)	Comments	Focus of analysis
Barker *et al.*, 2006b	E3MG, econometric	LBD and R&D	41	20	Cumulative investments and R&D spending determine energy demand via a technology index. Learning curves for energy technologies (electricity generation). Cumulative investments and R&D spending determine exports via a technology index.	Econometric model. Investments beyond baseline levels trigger a Keynesian multiplier effect. Sectoral R&D intensities stay constant overtime	Long-term costs of stabilization Income and production losses
Bollen, 2004	WorldScan CGE	R&D R&D (and occasionally LBD)	12	12	ETC magnifies income losses.	Includes international spillovers. No crowding-out effect	Compliance costs of Kyoto protocol
Buonanno *et al.*, 2003	FEEM-RICE optimal growth	R&D and LBD	1	8	Direct abatement costs are lower, but total costs are higher. ET ceilings have adverse effects on equity and efficiency.	Factor substitution in Cobb-Douglas production.	Impact of emissions trading (+ restrictions)
Bosetti *et al.*, 2006	FEEM-RICE	LBD	1	8	An index of energy technological change increases elasticity of substitution. Learning-by-doing in abatement and R&D investments raise the index. Energy technological change explicitly decreases carbon intensity.		Experimental model exploring high inertia.
Crassous *et al.*, 2006	IMACLIM-R GCE	R&D and LBD	1	5	Cumulative investments drive energy efficiency. Fuel prices drive energy efficiency in transportation and residential sector. Learning curves for energy technologies (electricity generation).	Endogenous labour productivity, capital deepening.	
Edenhofer *et al.*, 2006a	MIND Optimal growth	LBD	1	1	R&D investments improve energy efficiency. Factor substitution in a constant-elasticity-of-substitution (CES) production function. Carbon-free energy from backstop technologies (renewables) and CCS. Learning-by-doing for renewable energy. R&D investments in labour productivity. Learning-by-doing in resource extraction		
Gerlagh and Van der Zwaan, 2003	DEMETER Optimal growth	LBD	1	1	Costs are significantly lower. Transition to carbon-free energy. Lower tax profile. Early abatement	Results are sensitive to elasticity of substitution between technologies as well as to the learning rate for non-carbon energy	Optimal tax profile Optimal abatement profile Abatement costs
Gerlagh, 2006	DEMETER-1 CCS	LBD	1	1	Factor substitution in CES production. Carbon-free energy from renewables and CCS. Learning-by-doing for both and for fossil fuels.		

Note: See sources for details of models.

Sources: The table is derived from Sijm (2004) and Edenhofer et al. (2006b).

Table 11.15: *Continued*

Study	**Model**	**ETC channel**	**Number of production sectors**	**Number of regions**	**Major results (impact of ETC)**	**Comments**	**Focus of analysis**
Goulder and Mathai, 2000	Partial cost-function model with central planner	R&D LBD	1	1	Lower time profile of optimal carbon taxes. Impact on optimal abatement varies depending on ETC channel. Impact on overall costs and cumulative abatement varies, but may be quite large	Deterministic One instrument High aggregation Weak database	Optimal carbon tax profile Optimal abatement profile
Goulder and Schneider, 1999	CGE multisectoral model	R&D	7	1	Gross costs increase due to R&D crowding-out effect. Net benefits decrease.	Lack of empirical calibration Focus on U.S. Full ‘crowding-out’ effect	Abatement costs and benefits
Kverndokk *et al*., 2004	CGE model for a small open economy	LBD	1	1	Innovation subsidy is more important in the short term than a carbon tax. Innovation subsidy may lead to ‘picking a winner’ and ‘lock in’	Numerical illustrative model	Optimal timing and mixture of policy instruments Welfare effects of technology subsidies
Masui *et al*., 2006	AIM/Dynamic - Global	R&D	9	6	Factor substitution in CES production. Investments in energy conservation capital increase energy efficiency for coal, oil, gas and electricity. Carbon-free energy from backstop technology (nuclear/renewables).		Focus on energy efficiency with limited supply-side substitution.
Nordhaus, 2002	R&DICE optimal growth	R&D	1	8	ETC impact is lower than substitution impact and quite modest in early decades.	Deterministic Full ‘crowding-out’ of R&D High aggregation	Factor substitution versus ETC Carbon intensity Optimal carbon tax
Popp, 2004	ENTICE, optimal growth	R&D	1	1	Impact on cost is significant. Impact on emissions and global temperature is small	Partial crowding-out effect	Welfare costs Sensitivity analysis of R&D parameters
Popp, 2006a	ENTICE-BR	R&D	1	1	Factor substitution in Cobb-Douglas production. R&D investments in energy efficiency knowledge stock. Carbon-free energy from generic backstop technology	R&D investments lower price of energy from backstop technology.	
Rao et al., 2006	MESSAGE/ MACRO CGE	LBD	1	11	Carbon-free energy from backstop technologies (renewables, carbon scrubbing & sequestration). Learning curves for electricity generation and renewable hydrogen production	Factor substitution in CES production in MACRO.	
Rosendahl, 2004	Builds on Goulder and Mathai (2000)	LBD	1	2	Restrictions on emissions trading are cost-effective. Optimal carbon tax in Annex I region is increased with external spillovers	Outcomes are sensitive to learning rate, discount rate and slope of abatement curve	Optimal carbon tax (or permit price) over time in two regions Optimal emissions trading +restrictions

Table 11.16: *Learning rates (%) for electricity generating technologies in bottom-up energy system models*

	(a) One-factor learning curves				(b) Two-factor learning curves			
	ERIS	MARKAL	MERGE-ETL	MESSAGE	ERIS		MERGE-ETL	
Learning					LDR	LSR	LDR	LSR
Advanced coal	5	6	6	7	11	5	6	4
Natural gas combined cycle	10	11	11	15	24	2	11	1
New nuclear	5	4	4	7	4	2	4	2
Fuel cell	18	13	19	-	19	11	19	11
Wind power	8	11	12	15	16	7	12	6
Solar PV	18	19	19	28	25	10	19	10

Notes:
- Learning rates are defined as the percentage reduction in unit cost associated with a doubling of output. The acronym LDR stands for Learning-by-Doing Rates and LSR for Learning-by-Searching Rates in two-factor learning curves. In two-factor learning curves, cumulative capacity and cumulative R&D (or 'knowledge stock') are used to represent market experience (learning-by-doing) and knowledge accumulated through R&D activities, respectively.
- In MERGE-ETL, endogenous technological progress is applied to 8 energy technologies: six power plants (integrated coal gasification with combined cycle, gas, turbine with combined cycle, gas fuel cell, new nuclear designs, wind turbine and solar photovoltaic) and two plants producing hydrogen (from biomass and solar photovoltaic). Furthermore, compared to the original MERGE model, Bahn and Kypreos (2002; 2003a) have introduced two new power plants (using coal and gas) with CO2 capture and disposal in depleted oil and gas reservoirs. Like the MARKAL model, the ERIS model is a bottom-up energy system model. Both studies mentioned above cover six learning technologies. MESSAGE is also a bottom-up system engineering model. Like the other bottom-up energy system models, it determines how much of the available resources and technologies are used to satisfy a particular end-use demand, subject to various constraints, while minimizing total discounted energy system costs.
- For a review of the literature on learning curves, including 42 learning rates of energy technologies, see McDonald and Schrattenholzer, (2001).
- For a discussion and explanation of similar (and even wider) variations in estimated learning rates for wind power, see Söderholm and Sundqvist (2003) and Neij et al. (2003a; 2003b)

Sources: Sijm (2004), Messner (1997), Seebregts et al. (1999), Kypreos and Bahn (2003), and Barreto and Klaassen (2004), Barreto (2001), Barreto and Kypreos (2004), and Bahn and Kypreos (2003b).

By contrast with the results for top-down models, Sijm (2004) finds considerably more consistency among bottom-up models, where the effects of learning-by-doing typically reduce costs by 20% to 40% over the next half century, and by 60% to 80% over the next century. Importantly, however, these numbers are relative to a static technology alternative. To demonstrate the influence of this assumption, van Vuuren *et al.* (2004) run their model without a carbon constraint, but with learning, to identify a baseline level of technological change. Their approach roughly halves the estimated effect of ETC on mitigation.

The variations in the estimated effects of learning on costs in bottom-up models are driven primarily by variations in the assumed rate of learning (in other words, the extent of the reduction in costs for each doubling of installed capacity). Estimates of these rates vary, depending on whether they are assumed or econometrically estimated, and whether they derive from expert elicitation or historical studies. These learning rates vary between four leading models by as much as a factor of two for a given technology, as shown in Table 11.16.

The modelling of LBD is beset with problems. Model solutions become more complex because costs can fall indefinitely, depending on the extent of the market. Avoidance of multiple solutions typically requires the modeller to constrain the penetration of new technologies, making one element of the cost reduction effectively exogenous. Since many low-carbon technologies are compared with mature energy technologies early in the learning process, it becomes inevitable that their adoption spreads and that they eventually take over as carbon prices fall. Finally, the approach often assumes that diffusion and accompanying R&D are cost-free, although the investments required for the technologies with high learning rates may be comparable with those that are replaced.

In addition, the measurement of learning rates poses econometric problems. It is difficult to separate the effects of time trends, economies of scale and R&D from those of LBD (Isoard and Soria, 2001) and different functional forms and data periods yield different estimates, so the learning rates may be more uncertain than suggested by their treatment in the models. When controls for the effects of other variables are included, such as crowding-out effects, the influence of LBD in some models may become very small compared to the effect of R&D (Köhler *et al.*, 2006; Popp, 2006c).

A second survey of ETC effects on aggregate mitigation costs comes from the Innovation Modelling Comparison Project (IMCP) (Edenhofer *et al.*, 2006b). Rather than reviewing previous results, the IMCP engaged modelling teams to report results for specific concentration scenarios and, in particular, with and without ETC. Like the van Vuuren *et al.* (2004) study noted earlier, the IMCP creates a baseline technology path with ETC but without an explicit climate policy. This baseline technology path can then be either fixed, as autonomous technological change, or allowed to change in response to the climate policy.

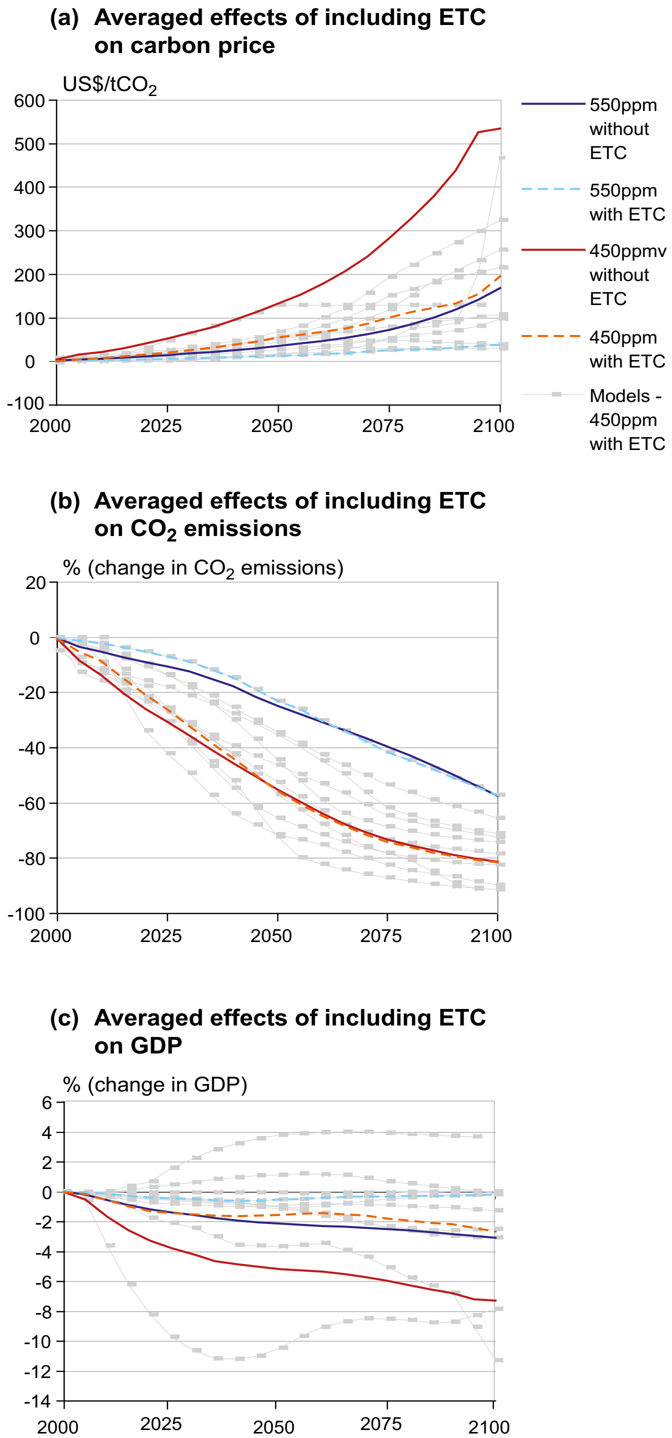

Figure 11.9: *Averaged effects of including ETC on carbon tax rates, CO_2 emissions and GDP: 9 global models 2000–2100 for the 450 ppm and 550 ppm CO_2-only stabilization scenarios*

Notes: The figures show the simple averages of results from 9 global models 2000–2100 for (a) carbon tax rates and emission permit prices in US$(2000)/$tCO_2$, (b) changes in CO_2 (% difference from base) and (c) changes in global GDP (% difference from base). The results are shown with and without endogenous technological change. The grey background lines show the range from the individual models for 450 ppm with ETC. See source for details of models.

Source: adapted from Edenhofer et al. (2006b).

Table 11.15 also summarizes the treatment of technological change in the IMCP models; in principle, the wide range of approaches provides additional confidence in the results when common patterns emerge. Like Sijm (2004), Edenhofer *et al.* (2006b) find that, while ETC reduces mitigation costs, there continues to be a wide range of quantitative results: some are close to zero and others generate substantial reductions in costs.

Figure 11.9 shows the effects of introducing ETC into the models for the 550 and 450 ppm CO_2 stabilization scenarios 2000–2100. The reductions in carbon prices and GDP are substantial for many studies in both stabilization cases when ETC is introduced. The effects on CO_2 reductions show that including ETC in the models leads to earlier reductions in emissions. It should be noted that the reduction of costs in IMCP models is not mainly driven by LBD. The assumptions about the crowding-out of conventional R&D by low-carbon R&D and the availability of mitigation options (models have different sets of options) are more important factors determining costs and mitigation profiles than LBD (Edenhofer *et al.*, 2006b, p.101–104). One major research challenge is to test the influence of these aspects of ETC on current technologies by econometric and backcasting methods, fitting the models to historical data.

Figure 11.9 emphasizes the range and the uncertainty of the results for induced technological change[16] from climate policies. The potential of ETC to reduce mitigation costs varies remarkably between different model types. For a 450 ppm CO_2-only concentration stabilization level at the upper end of the range, including ETC in the model reduces mitigation costs by about 90%, but at the lower end it makes no difference (Edenhofer *et al*. 2006b, p. 74). The averages also somewhat exaggerate the effects of ETC because there are other assumptions that affect the costs, as evident in a meta-analysis of the macro-economic costs of mitigation undertaken for the UK Treasury's Stern Review (Barker *et al.*, 2006b). An example is the use of tax/permit revenues, as discussed in 11.4.4 above. This study combines the IMCP results on costs with earlier data on post-SRES scenarios (Repetto and Austin, 1997; Morita *et al.*, 2000) so that the effects of other assumptions can be identified. The average effects of including ETC in the IMCP models by 2030 for pathways to 550 and 450 ppm CO_2-only are reduced from 1.1 and 2.7% of global GDP compared to baseline, as shown in Figure 11.9, to 0.4 and 1.3% respectively using the full equation of the meta-analysis, which allows for individual model outliers, time and scenario effects as well as the approaches and assumptions adopted by the modellers. In other words, allowing for technologies to respond to climate policies reduces the GDP costs of Category III stabilization, as estimated by the IMCP models, by 1.3% by 2030. Costs across models of 2.1% without ETC, but allowing for emissions trading and backstop technologies, are reduced to 0.8% GDP by 2030 with ETC. The ETC effects become more

16 When a model includes ETC, further change can generally be induced by economic policies. Hence the term 'induced technological change' (ITC); ITC cannot be studied within a model unless it simulates ETC. See Glossary on 'technological change'.

pronounced in the reduction of costs for later years and as the stabilization targets become more stringent, partly due to the associated extra increases in the required carbon prices.

Edenhofer *et al*. conclude that the results for effects of ETC depend on:

- baseline effects: baseline assumptions about the role of technology that generate relatively low emission scenarios can leave little opportunity for further ETC effects;
- the assumption of the inefficient use of resources in the baseline (distinct from market failure associated with greenhouse gas emissions and climate change): this provides opportunities for policy to improve otherwise inefficient private decisions and may even raise welfare. Spillovers were an example of this in the Sijm (2004) discussion; some simulations also include inefficient energy investment decisions.
- how the investment decision is modelled: recursive savings decisions, as opposed to foresight and intertemporal optimization, provide less opportunity for investment and R&D to expand. In the Sijm (2004) context, less responsiveness in aggregate investment and R&D implies more crowding-out.
- the modelling of substitution towards a backstop technology (such as a carbon-free energy source available at constant, albeit initially high, marginal cost): this can substantially affect the results. For example, if investment in the technology is endogenous and involves learning-by-doing, costs can fall dramatically. Popp (2006a, p.168) goes further, and shows that the addition of a backstop technology by itself can have a larger effect on mitigation costs than the addition of LBD. These results are also confirmed by the IMCP study (Edenhofer *et al.*, 2006b, p.214). However, investment in backstop technologies requires time-consistent policies (Montgomery and Smith, 2006). It is therefore debatable to what extent the indicated potential for cost reduction can be realized under real-world conditions where a global, long-term and time-consistent climate policy has yet to be implemented.

11.5.4 Modelling policies that induce technological change

Most of the studies discussed so far consider only how endogenous technological change affects the cost associated with correcting the market failure of damaging GHG emissions through market-based approaches to carbon taxes and/or emissions trading schemes. However, when spillovers from low-carbon innovation are introduced into the modelling of ETC, for example where the social rate of return exceeds the private rate of return from R&D because innovators cannot capture all the benefits of their investment, there is a second market failure. This implies that at least two instruments should be included for policy optimization (Clarke and Weyant, 2002, p.332; Fischer, 2003; Jaffe *et al.*, 2005). Even without the spillover effect, however, the advantage of models with endogenous technological change is their potential to model the effect of technology policy, distinct from mitigation policy, or in tandem. As discussed in Chapter 13, there has been increasing interest in such policies.

Surprising, few models have explored this question of mitigation versus technology policies, and they have focused instead on the cost assessments reviewed above. Those studies that have looked at this question find that technology policies alone tend to have smaller impacts on emissions than mitigation policies (Nordhaus, 2002; Fischer and Newell, 2004; Popp, 2006b; Yang and Nordhaus, 2006). In other words, it is more important to encourage the use of technologies than to encourage their development. On the other hand, with the existence of spillovers, technology policies alone may lead to larger welfare gains (Otto *et al.*, 2006). However, the same study points out that an even better policy (in terms of improving welfare) is to fix the R&D market failure throughout the economy. Given the difficulty in correcting the economy-wide market failure (e.g., through more effective patent protection or significantly increased government spending on research), it may be unrealistic to expect successful correction within the narrow area of energy R&D. This is true despite our ability to model such results.

However, this does open up the possibility of portfolios of policies utilizing some of the revenues from emission permit auctions to provide incentives for low-carbon technological innovation. An example is the approach of Masui *et al.* (2005) for Japan discussed in 11.3.4. Weber *et al.* (2005), using a long-run calibrated global growth model, conclude that '…increasing the fraction of carbon taxes recycled into subsidizing investments in mitigation technologies not only reduces global warming, but also enhances economic growth by freeing business resources, which are then available for investments in human and physical capital' (p. 321).

Unlike the studies that assess the effects of technology and mitigation policies on emissions and welfare in a simulation model, Popp (2002) examines the empirical effect of both energy prices and government spending on US patent activities in 11 energy technologies in the period 1970–1998. He finds that while energy prices have a swift and significant effect on shifting the mix of patents towards energy-related activities, government-sponsored energy R&D has no significant effect. While not addressing efforts to encourage private-sector R&D, this work casts doubt on the effectiveness of government-sponsored low-GHG research by itself as a mitigation option.

11.6 From medium-term to long-term mitigation costs and potentials

We now consider how the sectoral and macroeconomic analyses to 2030 relate to the stabilization-oriented studies of Chapter 3; this leads to a focus on the transitions in the second quarter of the century.

The section concludes by considering wider dimensions of timing and strategy.

11.6.1 Structural trends in the transition

Most studies suggest that GHG mitigation shifts over time from energy efficiency improvements to the decarbonization of supply. This is the clear trend in the global scenarios survey in Chapter 3 (Figure 3.23), and also in the time-path plots of energy against carbon intensity changes in the models in the IMCP studies (Edenhofer *et al.*, 2006b). It is also true of the national long-term studies surveyed in Chapter 3 (Table 3.7); of the detailed sectoral assessments of Chapters 4–10; and the IEA's ETP study (IEA, 2006a). In the first quarter of this century, the majority of global emission savings are associated with end-use savings in buildings and, to a lesser degree, in industry and transport. Moreover, despite important savings in electricity use in these sectors, economies in mitigation scenarios tend to become more electrified (Edmonds *et al.*, 2006). In the second quarter of this century, the degree of decarbonization of supplies starts to dominate efficiency savings as a result of a mix of strategies including CCS and diverse low-carbon energy sources. In the IEA study, the power sector consists of more than 50% non-fossil generation by 2050, and half of the remainder is made up of coal plants with CCS. The power sector still tends to dominate emission savings by 2030, even at lower carbon prices (see also Table 11.5), but obviously the degree of decarbonization is less.

There are two reasons for these trends. First, there are strong indications in the literature that improvements in energy efficiency with current technologies have greater potential at lower cost (see Chapters 5–7). This is apparent from the sectoral assessments summarized in Table 11.3, where energy efficiency accounts for nearly all the potential available at negative cost (particularly in buildings), and at least as much as the potential available from switching to lower carbon fuels and technologies in energy supply, for costs in the range up to 20 US\$/tCO_2 -eq. The second reason is that most models assume some inertia in the capital stock and diffusion of supply-side technologies, but not of many demand-side technologies. This slows down the penetration of low-carbon supply sources even when carbon prices rise enough (or when costs fall sufficiently) to make them economic. Some end-use technologies (such as appliances or vehicles) do have a capital lifetime that is much shorter than major supply-side investments; but there are very important caveats to this, as discussed below.

For the analysis of transitions during the first quarter of this century, then, most of the relevant modelling literature emphasizes, for stabilization between 650 and 550 ppm CO_2-eq (categories III and IV in table 3.5), energy supply and other sectors such as forestry in which mitigation potentials are dominated by long-lifetime, medium-cost options.

11.6.2 Carbon prices by 2030 and after in global stabilization studies

Many analyses in this report emphasize that efficient mitigation will require a mix of incentives: regulatory measures to overcome barriers to energy efficiency; funding and other support for innovation; and carbon prices to improve the economic attractiveness of energy efficiency and of low-carbon sources, and to provide incentives for low-carbon innovation and CCS. Most of the regulatory and R&D measures are sector-specific and are discussed in the respective sectoral chapters (4–10). Some implications of innovation processes are discussed below. Most global models focus on the additional costs of mitigation in the form of shadow prices or marginal costs, and the resulting changes that would be delivered by carbon prices. The carbon prices reached by 2030 are discussed in Section 11.4.4 above. The levels and trends in these prices are crucial to the transition processes.

The time trend of carbon prices after 2030 is important but specific to each model. Some models maintain a constant rate of price increase that largely reflects the discount rate employed (they establish an emissions time-path to reflect this). Two models in the EMF studies, for example, assume increases in carbon prices of about 5.5% per year and over 6% per year that are constant throughout the century. In this approach, carbon prices roughly treble over the period 2030–2050, and every two decades thereafter. Two models in the IMCP studies also use constant, and much lower, growth rates for prices that vary with the stabilization constraint. Edenhofer *et al.* (2006b) find that real carbon prices for stabilization targets rise with time in the early years for all models, with some models showing a decline in the optimal price after 2050 due to the accumulated effects of LBD and positive spillovers on economic growth. In these cases, a high-price policy in the earlier years may generate innovation that provides benefits in later years. In all these models, the *rates* of change frequently reflect intrinsic model parameters (notably the discount rate) and do not depend much on the stabilization target, which is reached by adjusting the starting carbon price instead. However, most but not all models with endogenous technical change have rates of carbon price increase that decline over time, and two models actually result in carbon price falls as technological systems mature.

A carbon price that rises over time is a natural feature of an efficient trajectory towards stabilization. The macro-economic cost depends on the *average* mitigation cost, which tends to rise more slowly and may decline with technical progress. The Stern review illustrates and explains scenarios in which rising carbon prices accompany declining average costs over time (Stern, 2006).

11.6.3 Price levels required for deep mid-century emission reductions: the wider evidence

Several other lines of evidence shed light on the carbon prices required to deliver transitions to deep mid-century CO_2

reductions. By contrast with the rising prices in most 'optimal' stabilization trajectories, some global models have been run with constant prices. Perhaps the most extensive, the IEA-ETP (2006a) study (MAP scenario), returns global CO_2 emissions roughly equal to 2005 levels by 2050 (more than halving emissions from reference). This is consistent with a trajectory towards category III stabilization at around 550 ppm CO_2-eq, with carbon prices rising to 24 US(2000)$/t$CO_2$ ($87/tC) by 2030 and then remaining fixed. The IEA study emphasizes the combination of end-use efficiency in buildings, industry and transport, together with the decarbonization of power generation as indicated. In other global studies that report sectoral results, the power sector dominates emission savings even in the weaker category IV scenarios. Some other models with detailed energy sectors do not force a constantly rising price or display periods of relatively stable prices along with stable or declining emissions.[17]

The carbon price results are consistent with the technology cost analyses in Chapter 4. These suggest that price levels in the 20–50 US$/t$CO_2$ range should make both CCS and a diversity of low-carbon power generation technologies economic on a global scale, with correspondingly large reduction potential attributed to the power sector in this cost range (Table 11.8). Newell, Jaffe & Stavins (2006) focus on the economics of CCS at prices within this range, noting that the carbon prices required will depend not only on CCS technology but also upon the reference alternative. Schumacher and Sands (2006) also focus on CCS but, in the context of the German energy system, conclude that a similar range is critical 'for CCS as well as advanced wind technologies to play a major role' (p. 3941). Riahi *et al.* (2004) project coal-based CCS costs up to 53 US$/tCO2. Corresponding reductions may accrue, whether a carbon price is considered to be implemented directly or as the incentive from certified emission reduction (CER) credits. Shrestha (2004) projects that 'business-as-usual' shares of coal in power generation by 2025 will be 46%, 78% and 85% in Vietnam, Sri Lanka and Thailand respectively, but an effective CER price of 20 US$/t$CO_2$ from 2006 onwards would reduce the share of coal to 18%, 0% and 45% respectively in the three countries by 2025. Natural gas and, to a lesser extent renewables, oil and electricity imports are the main beneficiaries.

The sectoral results from Chapters 4–10 (Table 11.3) suggest that carbon prices in the range 20–50 US$/t$CO_2$-eq could deliver substantial emission reductions from most sectors. Of the total potential identified below 100 US$/t$CO_2$-eq across all sectors, more than 80% is estimated to be economic at a cost below 50 US$/t$CO_2$-eq. Moreover, the lowest proportions are for agriculture (56%) and forestry (76%). Of the main sectors for which carbon cap-and-trade is being applied or considered at present, costs below 50 US$/t$CO_2$-eq account for 90% of the identified potential in energy supply and 86% in industry, whereas the proportion of the total below 20 US$/t$CO_2$-eq is about half (52%) and a quarter (27%) respectively for these sectors. This underlines the conclusion that carbon prices in the 20–50 US$/t$CO_2$-eq range would be critical to securing major changes in these principal industrial emitting sectors.

The bottom-up estimates of emission reductions available at less than 50 US$/t$CO_2$-eq for the total energy sector (supply, buildings, industry and transport) span 11.5–15 GtCO_2-eq/yr (Table 11.3, full range). This is strikingly similar to the range of CO_2 reductions by 2030 that global top-down studies consider to be necessary for trajectories consistent with stabilization in the Category III range (Figure 11.7 (a), in the range 25–40% reduction of CO_2 which, against the central baseline projection of 37–40 GtCO_2-eq (WEO/A2) for energy-related emissions that is used for the bottom-up estimates, equates to 10–16 GtCO_2-eq. Incidentally, this also equates to global emissions in 2030 that are roughly at present levels).

The capital stock lifetime of industrial and forestry systems (discussed further below) means that it takes some decades for the impact of a given carbon price to work its way through in terms of delivered reductions.[18] The assessment of timing is complicated by the fact that most global stabilization studies model a steadily rising price with 'perfect foresight'. However, Figure 11.7(c) confirms that almost all models project prices of *at least* 20 US$/t$CO_2$-eq by 2030, and some breach the 50 US$/t$CO_2$-eq level earlier in that decade, as might be expected in order to secure the required reductions by 2030. Applying the same statistical framing as Chapter 3, the analysis of price trends confirms that global carbon prices in more than 80% of the Category III stabilization studies cross within the range $20–50/t$CO_2$-eq during the decade 2020–30. These diverse strands of evidence therefore suggest a high level of confidence that carbon prices of 20–50 US$/t$CO_2$-eq (75–185 US$/tC-eq) reached globally in 2020–2030 and sustained or increased thereafter would deliver deep emission reductions by mid-century consistent with stabilization at about 550 ppm CO_2-eq (category III levels). To depict the impact in the models, such prices would have to be implemented in a stable and predictable manner and all investors would need to plan accordingly, at the discount rates embodied in the models.

Carbon prices at these levels would deliver these changes by largely decarbonizing the world's electricity systems, by providing a substantial incentive for additional energy efficiency and, if extended to land use, by providing major incentives to halt deforestation and reward afforestation.[19] By comparison,

17 Specifically, the GET-LFL 450 ppmCO_2 run has a peak in carbon prices at 37 US$/t$CO_2$ in 2020 followed by 2-3 decades of slight decline; the DNE21+ 450 ppmCO_2 run model rises sharply to about US$30/t$CO_2$ in 2020 followed by slow increase for a decade, then rises to 64 US$/t$CO_2$ in 2040 followed by slow increases out to 2070. See Hedenus, Azar and Lindgren (2006) and Sano et al. (2006) respectively.

18 The perfect foresight assumed in many of the global models complicates the assessment of timing; see 11.6.6 below.

19 The forestry chapter also notes that continuously rising carbon prices pose a problem in that forest sequestration might be deferred to gain more advantage from future higher prices; seen from this perspective, a more rapid carbon price rise followed by period of stable carbon prices could encourage more sequestration.

prices in the EU ETS in 2005 peaked close to 30 euros (about 40 US$)/$tCO_2$. Transition scenarios for non-energy sectors (in particular agriculture and deforestation) are reported in the respective sectoral chapters and in some of the multi-gas studies in Chapter 3.

Particularly in models that embody some economies of scale/learning-by-doing, prices maintained at such levels largely decarbonize the power sector over a period of decades. Some of the models display a second period with a similar pattern, later and at higher prices, as fuel cell-based transport matures and diffuses. In integrated Category III scenarios, such scenarios can also deliver more potential abatement in the transport sector (at a higher cost), partly because several of the low-carbon transport technologies depend on the prior availability of low-carbon electricity. Assumptions about the availability of petroleum and the costs of carbon-based 'backstop' liquid fuels also tend to be very important considerations in terms of the associated net costs (Edmonds *et al.*, 2004; Edenhofer *et al.*, 2006b; Hedenus *et al.*, 2006).

The price in the 20 to 50 US$/$tCO_2$ range required to deliver such changes – and answers to the questions of whether and by how much further carbon prices might need to rise in the longer term – depend upon developments in three other main areas: the contribution of voluntary and regulatory measures associated with energy efficiency; the extent and impact of complementary policies associated with innovation and infrastructure; and the credibility, stability and conviction that the private sector attributes to the price-based measures. We consider each in turn.

11.6.4 Complementary measures for deep emission reductions

The sectoral and multi-gas studies indicate that substantial emission savings are still available at low cost (< 20 US$/$tCO_2$), particularly from buildings (Chapter 6) and end-use efficiencies in a number of industrial sectors (Table 7.8); many governments are therefore already well embarked upon policies to exploit these low-cost opportunities. The IEA's World Energy Outlook (IEA, 2006b, Part 2) estimates that such measures could contribute a 16% reduction below the reference level by 2030. This would be an important contribution, but clearly insufficient to get close to halting or reversing global emissions growth in the absence of price-based measures.

Innovation will also be crucial for deep reductions by mid-century and in the longer term. Some of the technologies required to deliver ongoing emission reductions out to 2050 are already commercialized, but others (such as CCS) are not (see sector chapters). Deeper emission reductions will get more and more difficult over time without accelerated innovation bringing down costs, and increasing the diversity, of low-carbon options. Achieving the mitigation scenarios indicated therefore requires adequate progress in a range of relevant industries based on low-carbon technology (Weyant, 2004; IEA, 2006b). Chapter 2 has laid out the basic principles for low-carbon innovation and Chapter 3 the long-term role of technologies in stabilization scenarios. The sectoral chapters discussed the specific technologies and Section 11.5 covered the post-TAR modelling of induced technological change. This section briefly assesses the insights relating to innovation that are relevant to transitions in the second quarter of this century.

The conceptual relationship between such innovation investments and measures relating to carbon pricing is sketched out in Figure 11.10. Most low-carbon technologies (at least for supply) are currently much more expensive than carbon-based fuels. As R&D, investment and associated learning accumulates, their costs will decline, and market scale may grow. Rising carbon prices bring forward the time when they become competitive (indeed, many such technologies might never become competitive without carbon pricing). The faster the rise in carbon prices – particularly if industry can project such increases with confidence in a clear and stable policy environment – the sooner such technologies will become competitive and the greater the overall economic returns from the initial learning investment.

However, the literature also emphasizes that carbon pricing alone is insufficient. Sanden and Azar (2005) argue that carbon cap-and-trade is important for diffusion – 'picking technologies from the shelf' – but insufficient for innovation – 'replenishing the shelf'. Foxon (2003) emphasizes the interaction of environmental and knowledge market failures, arguing that this creates 'systemic' obstacles that require government action beyond simply fixing the two market failures (of climate damages and technology spillovers) independently.

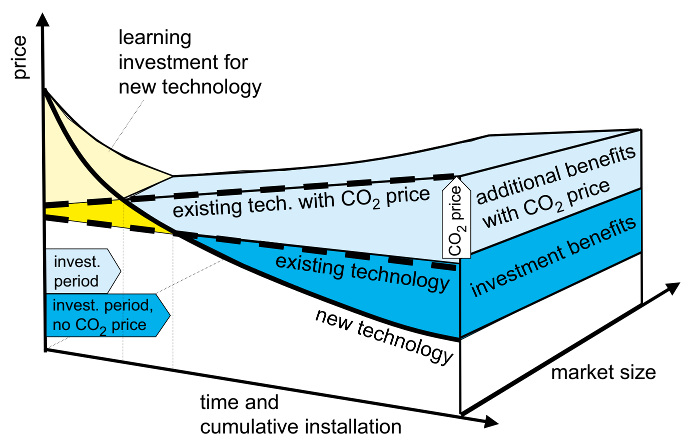

Figure 11.10: *Relationship between learning investments and carbon prices*

Notes: The figure illustrates cost relationships for new low-carbon technology as experience and scale build over time. Initially introduction is characterized by relatively high current costs and a very small market share, and requires a high unit rate for 'learning investment'. With increasing scale and learning, costs move towards existing, higher-carbon sources, the costs of which may also be declining, but more slowly. Rising carbon prices over time bring forward the time when the new technology may be competitive without additional support, and may greatly magnify the economic returns from the initial learning investment.

Source: Adapted with author's permission from Neuhoff (2004).

Table 11.17: *Observed and estimated lifetimes of major GHG-related capital stock*

Typical lifetime of capital stock			Structures with influence > 100 years
Less than 30 years	30-60 years	60-100 years	
Domestic appliances Water heating and HVAC systems Lighting Vehicles	Agriculture Mining Construction Food Paper Bulk chemicals Primary aluminium Other manufacturing	Glass manufacturing Cement manufacturing Steel manufacturing Metals-based durables	Roads Urban infrastructure Some buildings

Source: IEA (2000); industrial process data from Worrel and Biermans (2005).

There is therefore general consensus in the literature that, whilst emission reduction (including pricing) mechanisms are a necessary component for delivering such innovation, they are not sufficient: efficient innovation requires even more government action.

This underlines the complexity of measures required to drive adequate innovation. On the basis of four general lessons from US technology policy, Alic *et al.* (2003) derive various specific conclusions for action.[20] They break them down into direct R&D funding, support for deployment, and support for education and training. However, they also underline that 'technology policies alone cannot adequately respond to global climate change. They must be complemented by regulatory and/or energy pricing policies that create incentives for innovation and adoption of improved or alternative technologies … the technological response will depend critically on environmental and energy policies as well as technology polices.'

Philibert (2005) places climate technology policy in the context of the wider experience of US, European and IEA technology programmes and present initiatives, and discusses explicitly the international dimensions associated with globalization, export credit, diffusion, standards and explicit technology negotiations. Grubb (2004) outlines at least six different possible forms of international technology-oriented agreements that could, in principle, help to foster global moves towards lower-carbon energy structures (see Chapter 13).

The common theme in all these studies is the need for multiple and mutually supporting policies that combine technology push and pull across the various stages of the 'innovation chain', so as to foster more effective innovation and more rapid diffusion of low-carbon technologies, both nationally (the tax and subsidy regime for Japan discussed in 11.4.3.4, for example) and internationally. Most studies also emphasize the need for feedback enabling policy to learn from experience and experimentation – using 'learning-by-doing' in the process of policy development itself.

11.6.5 Capital stock and inertia determinants of transitions in the second quarter of the century

The scope for change, and the rate of transition, will be constrained by the inertia of the relevant systems. The IPCC SAR Summary for Policymakers noted that 'the choice of abatement paths involves balancing the economic risks of rapid abatement now (that premature capital stock retirement will later be proved unnecessary) against the corresponding risk of delay (that more rapid reduction will then be required, necessitating premature retirement of future capital stock).' Capital stock is therefore a central consideration.

The time scales of stock turnover vary enormously between different economic sectors, but appear to be very long for most greenhouse-gas emitting sectors. Typical investment time scales are several decades for forestry, coal mining and transporting facilities, oil & gas production, refineries, and power generation. On the demand side, observed time scales for typical industrial stock using energy are estimated to range from decades to a century (Worrell and Biermans, 2005; see Table 11.17). The time scales for other end-use infrastructure (e.g. processes, building stock, roads and rail) may be even longer, though components (such as heaters, cars) may have considerably faster turnover.

However, Lempert *et al.* (2002) caution against overly simplistic interpretations of nameplate lifetimes, emphasizing that they 'are not significant drivers [of retirement decisions] in the absence of policy or market incentives' and that 'capital has no fixed cycle'. This can be crucial to rates of decarbonization. A study of the US paper industry found that 'an increase in the rate of capital turnover is the most important factor in permanently changing carbon emission profiles and energy efficiency' (Davidsdottir and Ruth, 2004). Similarly, emission reductions in the UK power sector were largely driven by the retirement of old, inefficient coal plant during the 1990s, through sulphur regulations which meant plant owners were faced with the choice of either retrofitting stock or retiring it (Eyre, 2001).

20 Their four general lessons are: (i) Technology innovation is a complex process involving invention, development, adoption, learning and diffusion; (ii) Gains from new technologies are realized only with widespread adoption, a process that takes considerable time and typically depends on a lengthy sequence of incremental improvements that enhance performance and reduce costs; (iii) Technology learning is the essential step that paces adoption and diffusion; (iv) Technology innovation is a highly uncertain process.

Such micro-level 'tipping points' at which investment decisions need to be taken may offer ongoing opportunities for lower cost abatement.

Energy system inertia provides another dimension to the time scales involved. It has taken at least 50 years for each major energy source to move from 1% penetration to a major position in global supplies. Such long time scales – and the even longer periods associated with interactions between systems – imply that, for stabilization, higher inertia brings forward the date at which abatement must begin to start meeting any given constraint, and lowers the subsequent emissions trajectory (Ha-Duong *et al.*, 1997). In the context of stabilization at 550 ppm CO_2, van Vuuren *et al.* (2004) and Schwoon and Tol (2006) demonstrate that higher inertia in the energy system brings forward mitigation.[21]

However, beyond a certain point, inertia can also dramatically increase the cost of stabilization, particularly when infrastructure constraints are likely to limit the growth of new industries more than established ones. Manne & Richels (2004) illustrate that if global total contributions from new (renewable) power sources are limited to 1% by 2010 and treble each decade thereafter, the world has little choice other than to continue expanding carbon-intensive power systems out to around 2030. This feature appears to drive their finding of high costs for 450 ppm CO_2 stabilization, since much of this stock then has to be retired in subsequent decades to meet the constraint. This pattern contrasts sharply with some other studies, such the MIT study (McFarland *et al.*, 2004) that states an opposing time profile based partly upon the rapid deployment of natural gas plant, including CCS. Crassous *et al.* (2006) also find high costs by assuming that long-lived infrastructure construction continues without foresight over the century. If low-carbon transport technologies do not become available quickly enough, the economy is squeezed as carbon controls tighten. They also show that the early adoption of appropriate infrastructure avoids this squeeze and allows lower costs for carbon control. Drawing partly on more sociological literature, and the systems innovation literature (Unruh, 2002), tends to support a view that we are now 'locked in' to carbon-intensive systems, with profound implications: 'Carbon lock-in arises through technological, organizational, social and institutional co-evolution ... due to the self-referential nature of [this process], escape conditions are unlikely to be generated internally.'

Lock-in is less of a problem for new investment in rapidly developing countries where the CDM is currently the principal economic incentive to decarbonize new investments. The Shrestha (2004) study cited above illustrates how the structure of power sectors could be radically different depending upon the value of Certified Emission Reduction (CER) units. Their finding that an effective CER price of 20 US\$/tCO_2 from 2006 onwards could drive a radical switch of investment from new coal plants and primarily to natural gas and renewables in the three Asian countries studied would not only represent a large saving in CO_2 emission, but a totally different capital endowment that would sustain far lower emission trajectories after 2030. Again, this supports the conclusion that carbon prices of this order play a very important role, with their potential to forestall the construction of carbon-intensive stock in developing countries. Diverse policies that deter investment in long-lived carbon-intensive infrastructure and reward low-carbon investment may maintain options for low stabilization levels in Category I and II at lower costs.

At a global scale, van Vuuren *et al.* (2004) present a systematic set of results showing the effects of different time profiles for carbon prices in studies that combine the representation of inertia and induced innovation. A carbon price that rises linearly to 82 US\$/tCO_2 by 2030 reduces emissions by 40% by 2030 if the tax is introduced in 2020 and raised sharply, but by 55% if it is introduced in 2000 and increased more slowly. Van Vuuren *et al.* do not describe the impact on subsequent trajectories, but clearly the capital stock endowment differs substantially. Moreover, Lecocq *et al.* (1998) demonstrate that, in the face of uncertainty, an efficient approach may include greater effort directed at reducing investment in longer-lived carbon intensive infrastructure, over and above the incentives of any uniform carbon price.

Chapter 3 (Section 3.6) emphasizes the importance of 'hedging' strategies based upon sequential 'act-then-learn' decision-making. Mitigation over the next couple of decades that would be consistent with enabling stabilization at lower levels (Categories I, II or III) does not irrevocably commit the world to such levels. The major numerical addition to the literature in this vein appears to be that of Mori (2006). Using the MARIA model, he analyses optimal strategies to limit the global temperature increase to 2.5 ºC given uncertainty about climate sensitivity in the range of 1.5-4.5 ºC per doubling of CO_2-equivalent. When there is no uncertainty, only the above-average sensitivities require significant mitigation in the next few decades. In the context of uncertainty, however, the optimal strategy is to keep global emissions relatively constant at present levels until the uncertainty is resolved, after which they may rise or decline depending upon the findings.

11.6.6 Investment and incentive stability

The longevity of capital stock, projections of rapidly growing global emissions under 'business-as-usual', and the importance of industrial scale and learning in low-carbon technology industries all illustrate the central role of investment in relation to the climate change problem. As discussed in Chapter 4, the IEA (2004) estimates that about US\$20 trillion will be invested in energy supplies up to 2030, half to two-thirds of which is associated with power generation.

21 Specifically, van Vuuren *et al*. (2004, p. 599) state that including inertia 'results in a 10% reduction of global emissions after 5 years and 35% reduction after 30 years'.

Several major studies shed light upon the investment implications of low-carbon scenarios over the next few decades. The World Bank (2006) estimates that to 'significantly de-carbonize power production' would require incremental investments of 'up to' US $40bn per year globally, of which about US$30bn per year would be in non-OECD countries. However, in a comprehensive scenario, this would be offset by the reduced investment requirements resulting from improved end-use efficiency. The IEA WEO (2006b) 'alternative policy scenario' estimates that an increased investment of US$2.4 trillion in improved efficiency would be more than offset by US$3 trillion savings in supply investments. The more aggressive IEA 'Map' scenario (IEA, 2006a), that returns emissions to 2005 levels by 2050 (and is consistent with trajectories towards stabilization between 550 and 650 ppm CO_2-eq) as discussed above, reflects greater impact as a result of switching investment from more to less carbon-intensive paths. Investments across renewables, nuclear and CCS are projected of US$7.9 trillion, US$4.5 trillion of which is offset directly by the reduced investment required in fossil-fuel power plants. Most of the rest is offset by the reduced need for transmission and distribution investment and fuel savings arising from increased energy efficiency. The net additional cost for the Map scenario out to 2050 is only US$100 billion, about 0.5% of total projected sector investments.

Because the net cost estimates arise from balancing supply and demand, there is considerable uncertainty. The World Bank figure for incremental low-carbon power generation costs, for example, is much higher, at close to 10% of projected total investment costs, but does not fully offset these against end-use savings, or co-benefits. It is clear that low-carbon paths consistent with the IEA Map result of returning global CO_2 emissions to present levels involve a large redirection of investment, but the net additional cost based on this limited set of studies is likely to be less than 5–10% of the total investment requirements, and may be negligible. The studies collectively emphasize that the choice of path over the next few decades will have profound implications for the structure of capital stock, and its carbon intensity, well into the second half of this century and even beyond.

Much of this investment will come from the private sector. However, the associated literature emphasizes that current signals are inadequate and that the effectiveness of carbon pricing depends critically upon its credibility and predictability. For example, the perceived uncertainty with respect to the EU ETS after 2012 deters companies from investing on the basis of price. The credit agency Standard and Poor's (2005) state that 'this uncertainty has and will result in delays to investment decisions'. Sullivan and Blyth (2006) analyse the economics of investment in conditions of uncertainty and concur that the perceived uncertainties make it optimal for companies to defer investment and to keep old power plants running instead. This could even increase emissions. Consequently, the 'electricity or carbon prices required to stimulate investment in low-carbon technology may be higher than expected...' due to the uncertainties. This underlines the present gap between the modelling abstraction of perfect foresight, and the real-world uncertainties. The costs of mitigation will be reduced only to the extent that governments can make clear and credible commitments about future carbon controls that are sufficient for the private sector to see as 'bankable' in project investment appraisals.

11.6.7 Some generic features of long-term national studies

Finally, the rapidly growing number of national goals and strategies oriented towards securing ambitious CO_2 reduction goals, typically by 60–80% below present levels in industrialized countries, are relevant to the understanding of low-carbon transitions for the first half of this century. Some quantitative findings from some long-term national modelling studies have been summarized in Chapter 3, and some shorter-term studies earlier in this chapter.[22] Additional studies of long-term mitigation in developing countries are beginning to emerge (e.g. Jiang and Hu, 2006; Shukla *et al.*, 2006). The range and number of national analyses, scenarios and strategies devoted to mitigation targets is beyond the scope of this section but, in general, they suggest that there are a number of common 'high-level' features that underpin some main messages of the academic literature in terms of the need for a combination of:

- innovation-related action on all fronts, both R&D and market-based learning-by-doing stimulated by a variety of instruments;
- measures that establish a long-term, stable and predictable price for carbon to encourage lower carbon investment, particularly but not exclusively in power sector investments;
- measures that span the range of non-CO_2 gases so as to capture the 'low-hanging fruit' across the economy;
- measures relating to long-lived capital stock, especially buildings and energy infrastructure;
- institution- and option-building including considerations relating both to system structures, and policy experimentation with review processes to learn which are the most effective and efficient policies in delivering such radical long-term changes as knowledge about climate impacts accumulates.

11.7 International spillover effects

11.7.1 The nature and importance of spillover

Spillover effects of mitigation in a cross-sectoral perspective are the effects that mitigation policies and measures in

22 In addition to some of the specific economy-modelling studies referred to in preceding sections as indicated, strategic national studies written up in the academic literature include the Dutch COOL project (Treffers *et al.*, 2005), and analysis for long-term targets in the UK (Johnston *et al*., 2005) and Japan (Masui *et al*, 2006).

one country or group of countries have on sectors in other countries. (Inter-generational consequences, which are the effects of actions taken by the present generation on future generations, are covered in Chapter 2.) Spillover effects are an important element in the evaluation of environmental policies in economies globally linked through trade, foreign direct investment, technology transfer and information. Due to spillover effects, it is difficult to determine precisely the net mitigation potential for sectors and regions, and the effects of policies. An added complication is that the effects may be displaced over time. The measurement of the effects is also complex because effects are often indirect and secondary, although they can also accumulate to make local or regional mitigation action either ineffective or the source of global transformation. Much of the literature recognizes the existence of spillover effects. However, uncertainty and disagreement about time scale, cost, technology development, modelling approaches, policy and investment pathways lead to uncertainty about their extent and therefore the overall mitigation potentials.

The same spillover effect will be seen differently depending on the point of view adopted. Multiple differences between regions and nations imply differing, and perhaps contradictory views, about mitigation policies and their implementation. These differences emanate from the diverse and sometimes distinct natural endowments and social structures of those regions, as well as differences in the financial ability to cope with the costs that may be incurred as a result of the implementation of these policies. Methodologies that are developed for market-based industrialized economies may not be completely relevant for the economies of developing countries.

Some researchers who use general-equilibrium models (e.g. Babiker, 2005) conclude that spillover will, given certain assumptions, render mitigation action ineffective or worse if it is confined to Annex I countries. Other researchers (e.g. Grubb *et al.*, 2002a; Sijm *et al.*, 2004) argue that spillovers from Annex I action, implemented via induced technological change, could have substantial effects on sustainable development, with emission intensities from developing countries being a fraction of what they would be otherwise. 'However, no global models yet exist that could credibly quantify directly the process of global diffusion of induced technological change.' (Grubb *et al.*, 2002b, p.303). It is important to emphasize the uncertainties in estimating spillover effects, as well as uncertainties in estimating potential mitigation costs and benefits. In the modelling of spillovers through international trade, researchers rely on different approaches (bottom-up or top-down, for example), different assumptions (perfect/imperfect or 'Armington' substitution) and estimates of parameters when signs and magnitudes are disputed. Many of the models used to estimate the costs of mitigation focus on substitution effects and set aside information, policy and political spillovers, as well as the induced development and diffusion of technologies.

11.7.2 Carbon leakage

Carbon leakage is defined as the increase in CO_2 emissions outside the countries taking domestic mitigation action divided by the reduction in the emissions of these countries. It has been demonstrated that an increase in local fossil fuel prices resulting, for example, from mitigation policies may lead to the re-allocation of production to regions with less stringent mitigation rules (or with no rules at all), leading to higher emissions in those regions and therefore to carbon leakage. Furthermore, a decrease in global fossil fuel demand and resulting lower fossil fuel prices may lead to increased fossil fuel consumption in non-mitigating countries and therefore to carbon leakage as well. However, the investment climate in many developing countries may be such that they are not ready yet to take advantage of such leakage. Different emission constraints in different regions may also affect the technology choice and emission profiles in regions with fewer or no constraints because of the spillover of learning (this is discussed in Section 11.7.6).

Since the TAR, the literature has extended earlier-equilibrium analysis to include effects of trade liberalization and increasing returns in energy-intensive industries. A new empirical literature has also developed. The literature on carbon leakage since the TAR has introduced a new dimension to the analysis of the subject: the potential carbon leakage from projects intended for developing countries to help them reduce carbon emissions. One example is Gundimeda (2004) in the case of India (discussed in Section 11.7.3 below).

11.7.2.1 Equilibrium modelling of carbon leakage from the Kyoto Protocol

Paltsev (2001) uses a static global-equilibrium model GTAP-EG to analyse the effects of the Kyoto Protocol. He reports a leakage rate of 10.5%, with an uncertainty range of 5–15% covering different assumptions about aggregation, trade elasticities and capital mobility, but his main purpose is to trace back non-Annex B increases in CO_2 to their sources in the regions and sectors of Annex B. The chemicals and iron and steel sectors make the highest contributions (20% and 16% respectively), with the EU being the largest regional source (41% of total leakage). The highest bilateral leakage is from the EU to China (over 10% of the total). Kuik and Gerlagh (2003) use a similar GTAP-E model and conclude that, for Annex I Kyoto-style action, the main reason for leakage is the reduction in world energy prices, rather than substitution within Annex I. They find that the central estimate of 11% leakage is sensitive to assumptions about trade-substitution elasticities and fossil-fuel supply elasticities and to lower import tariffs under the Uruguay Round, and they state a range of 6% to 17% leakage.

In a more recent study, Babiker (2005), using a model with different assumptions about production and competition in the energy-intensive sector, reports a range of global leakage rates between 25% and 130%, depending on the assumptions adopted. The main reasons for the higher estimates are the inclusion of increasing returns to scale, strategic behaviour in the energy-intensive industry and the assumption of homogeneous products. Rates above 100% would imply that mitigation action in one region leads to more global GHG emissions rather than less.

However, other studies point to real world conditions that make these outcomes unlikely. Significant carbon leakage arises when internationally tradeable energy-intensive production moves abroad to non-abating regions. This is frequently referred to as a competitiveness concern. In industrialized countries, these sectors account for 15–20% of CO_2 emissions (IEA, 2004). Results with high leakage therefore reflect conditions in which countries implement policies that lead to most emission savings being obtained by industrial relocation (to areas of lower-cost, and in some cases less efficient, production), rather than in the less mobile sectors (such as power generation, domestic, services etc). In practice, most countries have tended to adjust policies to avoid any such outcome (for example through derogation, exemption or protection for such sectors).

Sijm *et al.* (2004) provide a literature review and an assessment of the potential effects of Annex I mitigation associated with the EU emissions trading scheme (ETS) for carbon leakage, and especially in developing countries. Technological spillovers discussed in this paper are considered in section 11.7.6 below. In the empirical analysis of effects in energy-intensive industries, the modelling studies reporting high leakage rates look at many other factors in addition to price competitiveness. They conclude that, in practice, carbon leakage is unlikely to be substantial because transport costs, local market conditions, product variety and incomplete information all favour local production. They argue that a simple indicator of carbon leakage is insufficient for policymaking. Szabo *et al.* (2006) report production leakage estimates of 29% by 2010 for cement given an EU ETS allowance price of about 50 US$/t$CO_2$ and a detailed model of the global industry. Leakage rates rise with the allowance price. More generally, Reinaud (2005) surveys estimates of leakage for energy-intensive industries (steel, cement, newsprint and aluminium) assuming the EU ETS. She comes to a similar conclusion to Sijm *et al.* (2004) and finds that, with the free allocation of CO_2 allowances, 'any leakage would be considerably lower than previously projected, at least in the near term.' (p. 10). However, 'the ambiguous results of the empirical studies in both positive and negative spillovers warrant further research in this field.' (p.179).

11.7.3 Spillover impact on sustainable development via the Kyoto mechanisms and compensation

The Kyoto mechanisms may also result in spillover effects that offset their additionality. Gundimeda (2004) considers how the clean development mechanism (CDM) might work in India. (The CDM is considered in detail in Chapter 13.) The paper examines the effects of CDM projects involving land-use change and forestry on the livelihoods of the rural poor. It concludes that, for CDM to be sustainable and to result in sustainable development for local people, three important criteria must be met: (1) in sequestration projects, local use of forestry (as firewood, for example) should also be an integral part of the project (2) management of the common lands by the rural poor through proper design of the rules for the sustenance of user groups; and (3) ensuring that the maximum revenue from carbon sequestration is channelled to the rural poor. 'Otherwise CDM would just result in either [carbon] leakage [e.g. through unplanned use of forestry for firewood] ... or have negative welfare implications for the poor' (p. 329).

Kemfert (2002) considers the spillover and competitiveness effects of the Kyoto mechanisms used separately (CDM, CDM with sinks, joint implementation (JI) and emissions trading (ET)) using a general-equilibrium model – WIAGEM – with Kyoto-style action (including the USA) continuing until 2050. The study shows the full welfare effect (% difference from business as usual) in 2050, broken down into the effects of domestic action, competitiveness and spillovers. It is notable that the mechanisms have a very small impact on welfare. At most, as an outlier, there is a 0.7% increase for countries in transition (REC) for emissions trading and a 0.1% decrease for the EU-15 for joint implementation. The CDM is found to improve welfare most in developing countries. However, the model does not include induced technological change or environmental co-benefits and it assumes full employment in all countries. If the CDM is assumed to result in more technological development, a more productive use of labour or an improvement in air or water quality, then the environmental and welfare effects in non-Annex I countries will be much larger than those reported.

Böhringer and Rutherford (2004) use a CGE model to assess the implications of UNFCCC articles 4.8 and 4.9 dealing with compensation. They conclude that 'spillover effects are an important consequence of multilateral carbon abatement policies. Emission mitigation by individual developed regions may not only significantly affect development and performance in non-abating developing countries, but may also cause large changes in the economic costs of emission abatement for other industrialized nations.' They estimate that the US should pay OPEC and Mexico estimated compensation of 0.7 billion US$ annually to offset the adverse impacts on these regions and that the EU should pay the same amount to the US to account for the positive spillover.

11.7.4 Impact of mitigation action on competitiveness (trade, investment, labour, sector structure)

The international competitiveness of economies and sectors is affected by mitigation action (see surveys by Boltho (1996), Adams (1997) and Barker and Köhler (1998)). In the long run, exchange rates change to compensate for a persistent loss of national competitiveness, but this is a general effect and particular sectors can become more or less competitive.

In the short run, the higher costs of fossil fuels lead to a loss in sectoral price competitiveness, especially in energy-intensive industries. The effects of domestic mitigation action on a region's international competitiveness are broken down by the literature into the effects on price and non-price competitiveness. This section covers price competitiveness, while technological spillover effects are discussed in Section 11.7.6 below.

In general, energy efficiency policies intended for GHG mitigation will tend to improve competitiveness (see Section 11.6.3 above). Zhang and Baranzini (2004) have reviewed empirical studies on the effects of Annex 1 action on international competitiveness. They conclude that 'empirical studies on existing carbon/energy taxes seem to indicate that competitive losses are not significant'. They therefore support the conclusions of the TAR, namely that 'reported effects on international competitiveness are very small and that at the firm and sector level, given well-designed policies, there will not be a significant loss of competitiveness from tax-based policies to achieve targets similar to those of the Kyoto Protocol.' (p.589). Baron and ECONEnergy (1997) looked at carbon prices similar to those expected to be necessary to implement the Kyoto Protocol (see 11.4.3.3). They report a static analysis of the cost increases from a tax of 27 US$/t$CO_2$ on four energy-intensive sectors in 9 OECD economies (iron and steel, other metals, paper and pulp, and chemicals). Average cost increases are very low – less than about 3% for most country sectors studied – with higher cost increases in Canada (all 4 sectors), Australia (both metal sectors) and Belgium (iron and steel).

However, action by Annex I governments (the EU, Denmark, Norway, Sweden, UK) have generally exempted or provided special treatment for energy-intensive industries. Babiker *et al.* (2003) suggest that this is a potentially expensive way of maintaining competitiveness, and recommend a tax and subsidy scheme instead. One reason for such exemptions being expensive is that, for a given target, non-exempt sectors require a higher tax rate, with mitigation at higher cost.

The impact of mitigation policies on trade within a region and between regions as a result of spillover is linked through capital flows from one country to another (within a region) or from one region to another, as individual investors and firms look for a higher rate of return on their investments which are considered by the receiving countries to be Foreign Direct Investment (FDI). Different market regulations and the flow of goods and services are influenced by mitigation policies, and the resulting spillover make 'measuring the welfare cost of climate change policies a real challenge, raising difficult issues of micro- and macro-economics: cost-benefit analysis on the one hand, foreign trade and international specialization on the second hand' (Bernard and Vielle, 2003). Partly for these reasons, the literature is sparse and the effects of different mitigation policies on FDI, trade, investment and labour market development within and between regions and any spillover effects are important areas for further research.

11.7.5 Effect of mitigation on energy prices

As discussed in 11.7.2, perhaps one of the most important ways in which spillovers from mitigation action in one region affect the others is through their effect on world energy prices. When a region reduces its fossil fuel demand as a result of mitigation policy, it will reduce the world demand for that commodity and so put downward pressure on the prices. Depending on responses from producers of fossil fuels, oil, gas or coal prices may fall, leading to losses of revenue for the producers, and lower import costs for the consumers. Demand for alternative, low-carbon fuels may increase. Three distinct spillover effects have been identified for non-mitigating countries. First, income for producers of fossil fuels will decline as the quantity sold is reduced, causing welfare losses and unemployment along with associated problems. Second, consuming nations will face lower prices for imported energy and may reduce subsidies or allow domestic energy prices to fall so that they tend to consume more, leading to carbon leakage as discussed above. Third, those non-mitigating countries producing low-carbon or alternative fuels will see an increase in demand and prices, with potentially positive effects on the markets for bioenergy.

11.7.5.1 Effects of Annex I action reported in the TAR

The TAR reviewed studies (based on CGE models with no induced technological change) of Annex I action in the form of a carbon tax or emissions trading schemes. The TAR (pp. 541–6) reported that, for abatement in Annex I, 'it was universally found that most non-Annex I economies that suffered welfare losses under uniform independent abatement suffered smaller welfare losses under emission trading' (p. 542). The magnitude of these losses is reduced under the less stringent Kyoto targets compared to assumptions about more stringent targets in pre-Kyoto studies. Some non-Annex I regions that would experience a welfare loss under the more stringent targets experience a mild welfare gain under the less stringent Kyoto targets. Similarities in regions identified as gainers and losers were quite marked. Oil-importing countries relying on exports of energy-intensive goods are gainers. Economies that rely on oil exports experience losses, with no clear-cut results for other countries.

The TAR considered the effect of OPEC acting as a cartel (pp. 543-4) and concludes that any OPEC response will have a modest effect on the loss of wealth to oil producers and the level on emission permit prices in mitigating regions. Analyses pertaining to the group of oil-exporting non-Annex I countries report costs differently, and the costs include, *inter alia*, reductions in projected oil revenues. Emissions trading reallocates mitigation to lower-cost options. The study reporting the lowest costs shows reductions of 0.2% of projected GDP with no emissions trading and less than 0.05% of projected GDP with Annex B emissions trading in 2010. The study reporting the highest costs shows a reduction of 25% in projected oil revenues with no emissions trading, and 13% in projected oil revenues with Annex B emissions trading in 2010. These studies did not consider policies and measures, other than Annex B emissions trading, that could lessen the impact on non-Annex I, oil-exporting countries, and therefore tend to overstate both the costs to these countries and overall costs. The effects on these countries can be further reduced by the removal of subsidies for fossil fuels, energy tax restructuring according to carbon content, the increased use of natural gas, and diversification of the economies of non-Annex I, oil-exporting countries (IPCC, 2001, p. 60).

11.7.5.2 Effect of mitigation on oil prices and oil exporters' revenues

The literature has hardly advanced since the TAR. GHG mitigation is expected to reduce oil prices, but the regional effects on GDP and welfare are mixed. Some studies point to gains by Annex I countries and losses to the developing countries, while others note losses in both of varying magnitudes, depending on different assumptions in the models. Studies that consider welfare gains/losses and international trade in Annex I countries also lead to mixed results, even if subsidies plus incentives and ancillary benefits are taken into account (Bernstein *et al.*, 1999; Pershing, 2000; Barnett *et al.*, 2004).

The highest modelling costs for implementing the Kyoto Protocol quoted by Barnett *et al.* (2004) for action in all Annex I countries are for OPEC: a 13% loss of oil revenues in the GCubed model (IPCC, 2001, p. 572). The scenarios underlying these costs assume Annex B action, including the USA and Australia, with a CO_2 tax but no allowances for non-CO_2 gases, sinks, targeted recycling of revenues or ancillary benefits. The outcome for OPEC is that its share of the world oil market falls compared to baseline projections. The authors argue that these costs will be lower following the Marrakech Accord; they are also lower because the US and Australia are not part of the Kyoto process, so the extent of mitigation action will be less than that modelled. All model estimates reviewed by Barnett *et al.* show that OPEC countries will see an increase in demand for oil but that this increase will be slowed by mitigation efforts following the Kyoto Protocol.

The use of OPEC market power could reduce negative effects, but this is uncertain (Barnett *et al.*, 2004, p. 2085). OPEC's World Energy Model assumes that OPEC production remains at baseline levels in the scenarios. This results in excess market supplies, since oil demand will be reduced. This leads to an estimate of OPEC losses of 63 billion US$ a year or about 10% of GDP, compared with 2% if supply is restricted in line with demand. Another scenario estimates the effect of an oil-price protection strategy, assuming that all major oil-producing countries in non-Annex B and in the former Soviet Union act together with OPEC. The conclusion is that OPEC losses would be substantially reduced. Another interesting feature of these results is that the losses as a percentage of 1999 GDP vary substantially across economies: from between 3.3% for Qatar to 0.07% for Indonesia by 2010.

Awerbuch and Sauter (2006) assess the effect of a 10% increase in the share of renewables in global electricity generation (which would reduce CO_2 by about 3% by 2030, compared with 16% in the IEA scenario). They suggest that the global oil price reduction would be in the range of 3 to 10%, with world GDP gains of 0.2 to 0.6%. Once again, the substantial increase expected in oil exporters' revenues would be reduced, although oil-importing countries would benefit.

Nearly all modelling studies that have been reviewed show more pronounced adverse effects on countries with high shares of oil output in GDP than on most of the Annex I countries taking the abatement measures.

11.7.6 Technological spillover

Mitigation action may lead to more advances in mitigation technologies. Transfer of these technologies, typically from industrialized nations to developing countries, is another avenue for spillover effects. However, as discussed in Chapter 2, effective transfer implies that developing countries have an active role in both the development and the adaptation of the technologies. The transfer also implies changes in flows of capital, production and trade between regions.

Sijm *et al.* (2004) assess the spillover effects of technological change. They divide the literature into two groups, depending on their 'top-down' or 'bottom-up' approach to modelling. (See the discussion on the topic in Section 11.3 above.) Most top-down modelling studies omit the effect or show it playing a minor role. The authors argue that the potential beneficial effect of technology transfer to developing countries arising from technological development brought about by Annex I action may be substantial for energy-intensive industries, but has so far not been quantified in a reliable manner. 'Even in a world of pricing CO_2 emissions, there is a good chance that net spillover effects are positive given the unexploited no-regret potentials and the technology and know-how transfer by foreign trade and educational impulses from Annex I countries to Non-Annex I countries.' (p. 179).

However, results from bottom-up and top-down models are strongly influenced by assumptions and data transformations and that lead to high levels of uncertainty. 'Innovation and technical progress are only portrayed superficially in the predominant environmental economic top-down models, and that the assumption of perfect factor substitution does not correctly mirror actual production conditions in many energy-intensive production sectors. Bottom-up models, on the other hand, neglect macroeconomic interdependencies between the modelled sector and the general economy.' (Lutz *et al.*, 2005). The effects of spillovers combined with learning-by-doing are explored specifically using bottom-up models by Barreto and Kypreos (2002) using MARKAL, and by Barreto and Klaassen (2004) using ERIS. They find that, owing to the presence of spillovers, the imposition of emission constraints in the Annex

I region may induce technological change and, hence, emission reductions in the non-Annex I region even when the latter region does not face emission constraints itself.

The existence of spillover effects also changes the theoretical conclusions in the economics literature. In the pure competition-equilibrium model, the most efficient policy is an equal rate of carbon tax for every sector and region. Rosendahl (2004) shows that, for maximum efficiency with spillovers and learning-by-doing, the carbon tax should be higher in those sectors and regions with the highest potential for technological progress. This is a general argument for stronger mitigation in those sectors and countries where technological progress is most likely to be accelerated by higher taxes on carbon use. In a game-theory context, with the shared benefits of R&D improving energy efficiencies, Kemfert (2004, p. 463) finds that 'full cooperation on climate control and technological improvements benefits all nations in comparison to a unilateral strategy.'

Although the technologies for CO_2 reduction in the electricity sectors are accessible, their dissemination still faces some challenges, especially in economies with low purchasing power and educational levels (Kumar *et al.*, 2003). An additional issue is that technology sharing by the fossil-fuel energy suppliers has been severely limited to date, probably due to the industrial organization of coal, oil and gas production, which is dominated by a few large private and state companies. Unlike, for example, new IT technologies, which quickly become industry standards, newly developed energy-related technology providing a competitive advantage generally becomes available to competitors slowly. However, modelling of the spillovers and the evolution of technologies, as well as structural changes in corporate management, require a better understanding of knowledge production and the knowledge transfer process within and between industries, and of the role and efficiency of transfer institutions such as universities, technology transfer centres and consultancy companies (Haag and Liedl, 2001).

11.8 Synergies and trade-offs with other policy areas

Anthropogenic GHG emissions are intricately linked to the structure of consumption patterns and levels of activity, which themselves are driven by a wide range of non-climate-related policy interests. These include policies on air quality, public health, energy security, poverty reduction, trade, FDI/investment regimes, industrial development, agriculture, population, urban and rural development, taxation and fiscal policies. There are therefore common drivers behind policies addressing economic development and poverty alleviation, employment, energy security, and local environmental protection on the one hand, and GHG mitigation on the other. Put another way, there are multiple drivers for actions that reduce emissions, and they produce multiple benefits.

Potential synergies and trade-offs between measures directed at non-climate objectives and GHG mitigation have been addressed by an increasing number of studies. The literature points out that, in most cases, climate mitigation is not the goal, but rather an outgrowth of efforts driven by economic, security, or local environmental concerns. The most promising policy approaches, then, will be those that capitalize on natural synergies between climate protection and development priorities to advance both simultaneously. Policies directed towards other environmental problems, such as air pollution, can often be adapted at low or no cost to reduce greenhouse gas emissions simultaneously. Such integration/policy coherence is especially relevant for developing countries, where economic and social development – not climate change mitigation – are the top priorities (Chandler *et al.*, 2002). Since the TAR, a wealth of new literature has addressed potential synergies and trade-offs between GHG mitigation and air pollution control, employment and energy security concerns.

11.8.1 Interaction between GHG mitigation and air pollution control

Many of the traditional air pollutants and GHGs have common sources. Their emissions interact in the atmosphere and, separately or jointly, they cause a variety of environmental effects at the local, regional and global scales. Since the TAR, a wealth of new literature has pointed out that capturing synergies and avoiding trade-offs when addressing the two problems simultaneously through a single set of technologies or policy measures offers potentially large cost reductions and additional benefits.

However, there are important differences at the temporal and spatial scales between air pollution control and climate change effects. Benefits from reduced air pollution are more certain; they occur earlier, and closer to the places where measures are taken, while climate impact is long-term and global. These mismatches of scales are mirrored by a separation of the current scientific and policy frameworks that address these problems (Swart *et al.*, 2004; Rypdal *et al.*, 2005).

Since the TAR, numerous studies have identified a variety of co-benefits of greenhouse gas mitigation on air pollution for industrialized and developing countries. In many cases, when measured using standard economic techniques, the health and environmental benefits add up to substantial fractions of the direct mitigation costs. More recent studies have found that decarbonization strategies generate significant direct cost savings because of reduced air pollution costs, highlighting the urgency of an integrated approach for greenhouse gas mitigation and air pollution control strategies.

11.8.1.1 Co-benefits of greenhouse gas mitigation on air pollution

A variety of analytical methods have been applied to identify co-benefits of greenhouse gas mitigation and air pollution.

Some assessments are entirely bottom-up and static, and focus on a single sector or sub-sector. Others include multi-sector or economy-wide general-equilibrium effects, taking a combination of bottom-up and top-down approaches. In addition, there are numerous methodological distinctions between studies. There are, for example, different baseline emission projections, air quality modelling techniques, health impact assessments, valuation methods, etc. These methodological differences, together with the scarcity of data, are a major source of uncertainties when estimating co-benefits. While the recent literature provides new insights into individual co-benefits (for example in the areas of health, agriculture, ecosystems, cost savings, etc.), it is still a challenge to derive a complete picture of total co-benefits.

11.8.1.2 Co-benefits for human health

Epidemiological studies have identified consistent associations between human health (mortality and morbidity) and exposure to fine particulate matter and ground-level ozone, both in industrialized and developing countries (WHO, 2003; HEI, 2004). Because the burning of fossil fuels is linked to both climate change and air pollution, lowering the amount of fuel combusted will lead to lower carbon emissions as well as lower health and environmental impacts from reduced emissions of air pollutants and their precursors.

Since the TAR, an increasing number of studies have demonstrated that carbon mitigation strategies result in significant benefits, not only as a result of improved air quality in cities, but also from reduced levels of regional air pollution. These benefits affect a larger share of the population and result from lower levels of secondary air pollutants. Although the literature employs a variety of methodological approaches, a consistent picture emerges from the studies conducted for industrialized regions in Europe and North America, as well as for developing countries in Latin America and Asia (see Table 11.18). Mitigation strategies aiming at moderate reductions of carbon emissions in the next 10 to 20 years (typically involving CO_2 reductions between 10 to 20% compared to the business-as-usual baseline) also reduce SO_2 emissions by 10 to 20%, and NO_x and PM emissions by 5 to 10%. The associated health impacts are substantial. They depend, *inter alia*, on the level at which air pollution emissions are controlled and how strongly the source sector contributes to population exposure. Studies calculate for Asian and Latin American countries several tens of thousands of premature deaths that could be avoided annually as a side-effect of moderate CO_2 mitigation strategies (Wang and Smith, 1999; Aunan *et al.*, 2003; O'Connor *et al.*, 2003; Vennemo *et al.*, 2006 for China; Bussolo and O'Connor, 2001 for India; Cifuentes *et al.*, 2001a; Dessus and O'Connor, 2003; McKinley *et al.*, 2005 for Latin America). Studies for Europe (Bye *et al.*, 2002; van Vuuren *et al.*, 2006), North America (Caton and Constable, 2000; Burtraw *et al.*, 2003) and Korea (Han, 2001; Joh *et al.*, 2003) reveal fewer, but nevertheless substantial, health benefits from moderate CO_2 mitigation strategies, typically in the order of several thousand premature deaths that could be avoided annually.

Several authors conducted an economic valuation of these health effects in order to arrive at a monetary quantification of the benefits, which can then be directly compared with mitigation costs. While the monetization of health benefits remains controversial, especially with respect to the monetary value attributed to mortality risks in an international context, calculated benefits range from 2 US\$/tCO_2 (Burtraw *et al.*, 2003; Joh *et al.*, 2003) up to a hundred or more US\$/tCO2 (Han, 2001; Aunan *et al.*, 2004; Morgenstern *et al.*, 2004). This wide range is partially explained by differences in methodological approaches. The lower estimates emerge from studies that consider health impacts from only one air pollutant (such as SO_2 or NO_x), while the higher estimates cover multiple pollutants, including fine particulate matter, which has been recently shown to have the greatest impact. Differences in mortality evaluation methods and results also constitute a substantial source of discrepancy in the estimated value of health impact as well.

The benefits also largely depend on the source sector in which the mitigation measure is implemented. Decarbonization strategies that reduce fossil fuel consumption in sectors with a strong impact on population exposure (such as domestic stoves for heating and cooking, especially in developing countries) can typically result in health benefits that are 40 times greater than a reduction in emissions from centralized facilities with high stacks such as power plants (Wang and Smith, 1999). Mestl *et al.*, (2005) show that the local health benefits of reducing emissions from power plants in China are small compared to abating emissions from area sources and small industrial boilers. A third factor is the extent to which air pollution emission controls have already been applied. Health benefits are larger in countries and sectors where pollutants are normally emitted in an uncontrolled way, for instance for small combustion sources in developing countries.

Despite the large range of benefit estimates, all studies agree that monetized health benefits make up a substantial fraction of mitigation costs. Depending on the stringency of the mitigation level, the source sector, the measure and the monetary value attributed to mortality risks, health benefits range from 30 to 50% of estimated mitigation costs (Burtraw *et al.*, 2003; Proost and Regemorter, 2003) up to a factor of three to four (Aunan *et al.*, 2004; McKinley *et al.*, 2005). Particularly in developing countries, several of the studies reviewed indicate that there is scope for measures with benefits that exceed mitigation costs (no-regret measures).

Such potential for no-regret measures in developing countries are consistently confirmed by studies applying a general-equilibrium modelling approach, which takes into account economic feedback within the economy. Bussolo & O'Connor (2001) estimate that the potential for CO_2 mitigation in India for 2010, without a net loss in welfare, is between 13

Table 11.18: *Implications for air-quality co-benefits from GHG mitigation studies*

Authors	Country	Target year	Sector	Delta CO_2 emissions	Carbon price (US$/$tCO_2$)	Impact on air pollutant emissions	Difference in health impacts	Health benefits (US$/$tCO_2$)	Difference in air pollution control costs	Total benefits
Burtraw *et al.*, 2003	US	2010	Power sector		7			2	1–2 US$/ tCO_2	
Caton and Constable, 2000	Canada	2010	All sectors	-9%		SO_2: -9% NO_x: -7% PM: -1%		11 (12–77)		
Wang & Smith, 1999	China	2020	Power sector	15% below BAU	11		4,400-5,200 premature deaths per year			
		2020	Domestic sector	15% below BAU	1.4		120,000-180,000 premature deaths per year			
O'Connor, 2003	China	2010	All sources	15% below BAU						No loss in net welfare
Aunan *et al.*, 2004	Shanxi, China	2000	Cogeneration		-30 (net benefit)			32		
			Modified boiler design		-6			23		
			Boiler replacement		-3			32		
			Improved boiler management		9			32		
			Coal washing		22			86		
			Briquetting		27			118		
Kan *et al.*, 2004	Shanghai, China	2010	All sources		24		608–5144 premature deaths per year			
		2020					1189–10462 premature deaths per year			
Li, 2006	Thailand									45% lower welfare losses
Vennemo *et al.*, 2006	China	2008-2012	Power production, industrial boilers, steel making, cement, chemical industry	80-236 $MtCO_2$ annually	6 for the 80 Mt potential; unknown for the upper estimate	SO_2: 0.5–3 million tons; TSP: 0.2–1.6 million tons	2700 - 38000 lives saved annually (34–161 lives saved per million tons CO_2)	Avoided deaths: 4.1–20; all health effects: 5–44		

Note: The carbon prices in the table are indicative only. They have been converted to US$/$tCO_2$, but the implicit price bases in the original studies vary and may not be quoted or available.

Table 11.18: *Continued*

Authors	**Country**	**Target year**	**Sector**	**Delta CO_2 emissions**	**Carbon price (US$/$tCO_2$)**	**Impact on air pollutant emissions**	**Difference in health impacts**	**Health benefits (US$/$tCO_2$)**	**Difference in air pollution control costs**	**Total benefits**
Morgenstern, 2004	Taiyuan, China		Phase-out of small boilers	80%		-95%		38–175 US$/ tCO_2		
Bussolo & O'Connor, 2001	India		All sources	13-23% below BAU						No welfare loss
Joh *et al.*, 2003	Korea	2020	All sources	5–15%				2 US$/$tCO_2$		
Han, 2001	Korea	2010	All sources	-10%		SO_2: -10% NO_x: -9.6% PM: -10%		58–76		
Van Vuuren, 2006	Europe	2020	All sources	4–7%		SO_2: 5–14%				
Syri *et al.* 2001	EU-15	2010	All sources	-8%		SO_2: 13-40% NO_x: 10–15%			-10%	
Proost *et al.*, 2003	Belgium	2010-2030	All sources	7–15%						30% of mitigation costs
Syri *et al.*, 2002	Finland	2010	All sources	Kyoto compliance		SO_2: -10% NO_x : -5% PM: -5%				
Bye *et al.*, 2002	Nordic countries		All sources	20–30%					9-22 US$/ tCO_2	0.4% to 1.2% of GDP
Cifuentes *et al.*, 2001a , 2001b	Mexico City, Santiago, Sao Paulo, New York	2020					64,000 premature deaths per year			
West *et al.*, 2004	Mexico City	2010	18 GHG measures (mainly transport)	9%		PM10: -1.3% NO_x: 1.4% HC: 3.2%				
McKinley *et al.*, 2005	Mexico City	2020	5 mitigation options	0.8 Mt C/yr (1.1%)			100 premature deaths per year			
Dessus *et al.*, 2003	Santiago de Chile	2010		20% below BAU						No welfare loss

and 23% of the emissions for a business-as-usual scenario. For China, this potential has been estimated by O'Connor (2003) for 2010 at 15 to 20%, and Dessus and O'Connor (2003) arrive at a figure of 20% for Chile compared with the business-as-usual emissions in 2010. Li (2002; 2006) finds for Thailand that inclusion of health impacts reduces the negative impacts on GDP of a carbon tax by 45%, improving welfare for households and resulting in cleaner producers.

11.8.1.3 Co-benefits for agricultural production

While a strong body of literature demonstrates that there are important co-benefits from GHG mitigation and health benefits from improved air quality, there has been less research addressing co-benefits from improved agricultural production**.** The potential positive, long-term, effect of higher CO_2 concentrations on plants can be counteracted by short-term damage from increased air pollution. The effects of tropospheric ozone exposure on plant tissues and crop yields are well established, and the scientific literature has already been reviewed in US EPA (1996) and EC (1999). Chameides *et al.* (1994) estimate that 10–35% of the world's grain production is in locations where ozone exposure may reduce crop yields. Surface ozone levels are sensitive to, *inter alia*, NO_x and VOC emissions from fossil-fuel-burning power plants, industrial boilers, motor vehicle exhaust, gasoline retail outlets, and N-fertilizer-induced soil emissions of NO_x.

Using an atmospheric ozone formation model and an economic general-equilibrium model, O'Connor *et al.* (2003) find, for a CO_2 mitigation strategy in China, that the monetary benefits from increased agricultural productivity due to lower ground-level ozone are comparable to the health benefits. Together, these benefits would allow China a 15–20% CO_2 reduction without suffering a welfare loss. Agricultural benefits have important distributional implications. When agricultural effects are not taken into consideration, poor rural households experience welfare losses from carbon mitigation even at low levels of abatement. Once agricultural effects are considered, rural households in this study enjoy welfare gains up to a ten percent abatement rate. So while a purely health-based measure of ancillary benefits tends to show benefits from a climate commitment to be urban-biased, a broader definition of benefits alters the picture considerably.

11.8.1.4 Co-benefits for natural ecosystems

A few studies have pointed out co-benefits of decarbonization strategies from reduced air pollution on natural ecosystems**.** VanVuuren *et al.* (2006) estimate that, in Europe, compared to an energy policy without climate targets, the implementation of the Kyoto protocol would bring acid deposition below the critical loads in an additional 0.6 to 1.4 million hectares of forest ecosystems, and that an additional 2.2 to 4.1 million hectares would be protected from excess nitrogen deposition. The exact area will depend on the actual use of flexible instruments, which allow for spatial flexibility in the implementation of mitigation measures but do not take into consideration the environmental sensitivities of ecosystems that are affected by the associated air pollution emissions. Syri *et al.* obtained similar results (2001).

While sustainability and the protection of natural ecosystem have turned out to be important policy drivers in the past (for example in the case of the emission reduction protocols of the Convention on Long-range Transboundary Air Pollution for Europe), there is no generally accepted method for quantifying the monetary value of the existence and function of natural ecosystems. It therefore continues to be difficult to include co-benefits on natural ecosystems in a comprehensive monetary cost-benefit calculation of mitigation measures.

11.8.1.5 Avoidance of air-pollution control costs

As pointed out above, the co-benefits from CO_2 mitigation on air pollution impacts have been found to be largest in developing countries, where air pollutants are often emitted without stringent emission control legislation. Most industrialized countries, however, enforce comprehensive legal frameworks to safeguard local air quality, and these frameworks include source-specific performance standards, national or sectoral emission caps, and ambient air quality criteria.

An increasing number of studies demonstrate significant savings from GHG mitigation strategies on the compliance costs for such air quality legislation. When there are source-specific performance standards, fewer plants burning fossil fuels also imply fewer air pollution control devices. If overall emissions in a country are capped, for example through national emission ceilings in the European Union, or by the obligations of the Gothenburg Protocol of the Convention on Long-range Transboundary Air Pollution, the lower consumption of carbonaceous fuels also reduces the costs for complying with such emission ceilings. This is particularly important since, in these conditions, countries can avoid implementing more expensive air pollution control measures. A similar situation applies when there are legal systems requiring compliance with ambient air quality standards. Carbon mitigation strategies that reduce the levels of polluting activities alleviate control requirements for the remaining sources.

Several studies consistently demonstrate the significance of such cost savings for different countries. Syri *et al.* (2001) found that low-carbon strategies could reduce air pollution control costs for complying with the EU national emission ceilings in 2010 by 10 to 20%, depending on the extent to which flexible mechanisms of the Kyoto protocol are applied. For the long-term perspective until 2100, van Harmelen *et al.* (2002) found air pollution (SO_2 and NO_x) control costs without climate policy objectives to be comparable or, in some periods, even higher than the total costs of an integrated strategy that also includes CO_2 mitigation.

The impact of flexible mechanisms on cost savings has been further explored by van Vuuren *et al.* (2006) for Western European countries. If the Kyoto obligations were to be implemented through domestic action alone, CO_2 mitigation measures amounting to 17 billion US$ per year would allow savings on air pollution control costs of 9.4 billion US$ per year. By contrast, if these countries reached compliance by buying permits for 4 billion US$ per year from outside and implemented domestic measures amounting to 1.4 billion US$ per year, air pollution control costs would decline by 2.4 billion US$ per year in these countries. At the same time, the other European countries selling permits (for 4.3 billion US$ per year) would save an additional 0.7 billion US$ per year on their own air pollution control costs due to the additional carbon mitigation measures.

A study of the United States by EIA (1998) estimated that, for a 31% reduction in CO_2 emissions, the associated decline in SO_2 emissions would be so large that the prices for SO_2 allowances will be driven to zero. Burtraw *et al.* (2003) calculated, for a 7 US$/t$CO_2$ carbon tax, savings of 1–2 US$/t$CO_2$. Their finding was that these savings would be generated by reduced investments in SO_2 and NO_x abatement in order to comply with emission caps.

These cost savings are immediate, they do not depend on controversial judgments on the monetary value of mortality risks, and they can be directly harvested by the actors who need to invest in mitigation measures. They therefore add an important component to a comprehensive assessment of the co-benefits of mitigation strategies. While these cost savings predominantly emerge at present in industrialized countries with elaborate air quality regulations, they will gain increasing importance in developing countries as the latter also progressively implement action to achieve sustainable levels of local air quality.

11.8.1.6 The need for an integrated approach

While the studies above adopt different methodological approaches, there is general consensus for all the world regions analyzed that near-term benefits from GHG reductions on human health, agriculture and natural ecosystems can be substantial, both in industrialized and developing countries. In addition, decarbonization strategies lead to reduced air pollution control costs. However, the benefits are highly dependent on the technologies and sectors chosen. In developing countries, many of the benefits could result from improvements to the efficiency of, or switching away from, traditional uses of coal and biomass. Such near-term secondary benefits of GHG control provide an opportunity for a true no-regrets GHG reduction policy in which substantial advantages accrue even if the impact of human-induced climate change itself turns out to be less than current projections indicate.

Climate mitigation policies, if developed independently from air pollution policies, will either constrain or reinforce air pollution policies, and vice-versa. The efficiency of a framework depends on the choice and design of the policy instruments, in particular on how well they are integrated. From an economic perspective, policies that may not be regarded as cost-effective from a climate change or an air pollution perspective alone may be found to be cost-effective if both aspects are considered. So piecemeal regulatory treatment of individual pollutants, rather than a comprehensive approach, could lead to stranded investments in equipment (for example, if new conventional air pollutant standards are put into place in advance of carbon dioxide controls at power plants) (Lempert *et al.*, 2002).

On the basis of recent insights into atmospheric chemistry and health impacts, the literature has identified several concrete options for harvesting synergies between air pollution control and GHG mitigation, and has identified other options that induce undesired trade-offs.

The co-control of emissions – in other words controlling two or more distinct pollutants (or gases) that tend to emanate from a single source through a single set of technologies or policy measures – is a key element of any integrated approach. Air pollutants and GHGs are often emitted by the same sources and so changes in the activity levels of these sources affect both types of emissions. Technical emission control measures aiming at the reduction of one type of emissions from a particular source may reduce or increase the emissions of other substances.

In the energy sector, efficiency improvements and the increased use of natural gas can address both problems (resulting in synergy effects), while the desulphurization of flue gases reduces sulphur emissions but can – to a limited extent – increase carbon dioxide emissions (trade-offs). There are also trade-offs for NO_x control measures for vehicles and nitric acid plants, where increases in N_2O emissions are possible. Concerns have been expressed that measures that improve the local environmental performance of coal in electricity generation might result in a lock-in of coal technologies that will make it more difficult to mitigate CO_2 emissions (McDonald, 1999; Unruh, 2000).

In agriculture, some specific measures to abate ammonia emissions could enhance nitrous oxide and/or methane emissions, while other types of measures could reduce the latter. For Europe, Brink *et al.* (2001) have estimated that abating agricultural emissions of ammonia (NH_3) may cause releases of N_2O from this sector that are up to 15% higher than they would be without NH_3 control. There may be substantial differences in the observed effects between various countries, depending on the extent and type of NH_3 control options applied.

11.8.1.7 Methane/ozone

Analyzing non-CO_2 greenhouse gases broadens the scope of climate protection and expands opportunities for synergies involving local pollutants since the co-emission of local pollutants and greenhouse gases vary depending on the type of greenhouse gas considered. For example, in addition to its role as a potent GHG, methane acts as a precursor to tropospheric ozone, together with emissions of nitrogen oxides (NO_x), volatile organic compounds (VOC) and carbon monoxide (CO). Whereas reductions in NO_x and VOC emissions influence local surface ozone concentrations, reductions in methane emissions lower the global ozone background and improve surface air quality everywhere. So reducing methane emissions addresses simultaneously both the pursuit of improved ozone air quality and climate change mitigation objectives (Fiore *et al.*, 2002; Dentener *et al.*, 2004). For instance, West *et al.* (2006) estimate the decreases in premature human mortality that can be attributed to lower surface ozone concentrations resulting from methane mitigation. Reducing global anthropogenic methane emissions by 20% starting in 2010 would prevent approximately 30,000 premature all-cause mortalities globally in 2030, and approximately 370,000 between 2010 and 2030. If avoided mortalities are valued at $1 million each, the benefit of 12 US$/t$CO_2$-equivalent exceeds the marginal cost of the methane reduction. These benefits of climate-motivated methane emission reductions are comparable to those estimated in other studies for CO_2.

A review of health impact studies conducted by the World Health Organization finds evidence for negative effects of ozone on human health even at very low concentrations (WHO, 2003). This has turned the attention of air quality management away from ozone peak episodes towards long-term concentrations, both in the industrialized and the developing world. Long-term concentration levels are driven by emissions at the hemisphere scale and are strongly influenced by atmospheric processes involving methane.

Tropospheric ozone, in addition to its health and vegetation effects, is also a potent GHG (IPCC, 2007a). So ozone reductions will not only result in benefits for local air quality, but also reduce radiative forcing. Further work will be necessary to identify mitigation portfolios that include hemispheric or global methane mitigation on the one hand and control of the local ozone precursor emissions on the other in order to maximize benefits for the global radiation balance and local air quality.

11.8.1.8 Biomass

Particularly relevant trade-offs have been identified for GHG mitigation strategies that enhance the use of biofuels and diesel. Biofuels from sustainably-grown biomass are considered to be carbon-neutral. They have therefore been proposed as an important element in decarbonization strategies. However, their combustion in household devices under uncontrolled conditions releases large amounts of fine particulate matter and volatile organic compounds, which cause significant negative health impacts. For instance, Streets and Aunan (2005) estimate that the combustion of coal and biofuels in Chinese households has contributed to about 10–15% of the total global emissions of black carbon during the past two decades. Emissions from these sources have been identified as the major source of health effects from air pollution in developing countries, adding the highest burden of disease (Smith *et al.*, 2004). In addition to the negative health impacts of traditional biomass combustion, there are concerns about the effectiveness of the combustion of biomass in stoves as a climate change mitigation measure due to the loss of efficiency compared to stoves using fossil fuels (Edwards *et al.*, 2004).

However, the controlled combustion of biomass with stringent air quality measures would prevent a substantial proportion of any toxic emissions. This would sometimes be accompanied by increases in efficiency. Furthermore, ethanol and biodiesel can be produced from biomass in medium-to-large industrial installations with air quality control measures that prevent negative health impacts.

11.8.1.9 Diesel

Similar concerns apply to attempts to reduce CO_2 emissions through the replacement of gasoline vehicles by more energy-efficient diesel vehicles. Without the most advanced particle filters, that require very-low-sulphur fuel which is not available everywhere, diesel vehicles are a major contributor to population exposure to fine particulate matter, especially of $PM_{2.5}$ and finer. Diesel particles have been shown to be more aggressive than other types of particles, and are also associated with cancer (HEI, 1999). Mitigation strategies that increase the use of diesel vehicles without appropriate emission control devices counteract efforts to manage air quality. At the same time, concern has been expressed in the literature about the radiative effects of the emissions of black carbon and organic matter from diesel vehicles, which might offset the gains from lower CO2 emissions (Jacobson, 2002). Although both the US and the EU are moving towards very stringent emission standards for diesel engines, their adoption by the rest of the world may be delayed by years.

11.8.1.10 Practical examples of integrated strategies

The realization of co-benefits has moved beyond a notion or an analytical exercise and is actually reflected increasingly in national regulations and international treaties.

US EPA operates a programme called 'Integrated Environmental Strategies' that is designed to build capacity to conceptualize co-control measures, analyze their co-benefit potential, and encourage the implementation of promising measures in developing countries. The programme has been active in eight developing countries, resulted in numerous assessments at the urban and national levels of co-benefits, and has helped influence policies leading to efficient measures that address local pollution and GHGs together. The programme is outlined in detail in US EPA (2005).

The European Commission, in its European Climate Change (ECCP) and Clean Air For Europe (CAFE) programmes, explores the interactions between the European Union's climate change and air pollution strategies and examines harmonized strategies that maximize the synergies between both policy areas (CEC, 2005).

The 1987 Montreal Protocol on Subsances that deplete the Ozone Layer mandates the phase-out of ozone-depleting substances, CFCs, halons, HBFCs, HCFCs, and methyl bromide. Some of the alternatives to these products, which are used primarily in refrigeration and in air conditioning, and for producing insulating foam, have significant GWPs although these are, in many cases, less than those for the CFCs and HCFCs. They also can improve the energy efficiency of some equipment and products in which they are used. In order to investigate the link between ozone depletion and climate change, a Special Report was produced by IPCC and the Technology and Economic Assessment Panel (TEAP) of the Montreal Protocol (IPCC & TEAP, 2005).

11.8.2 Impacts of GHG mitigation on employment

A number of studies point out that investments in greenhouse gas mitigation could have a greater impact on employment than investments in conventional technologies. The net impact on employment in Europe in the manufacturing and construction industries of a 1% annual improvement in energy efficiency has been shown to induce a positive effect on total employment (Jeeninga *et al.*, 1999). The effect has been shown to be substantially positive, even after taking into account all direct and indirect macro-economic factors such as the reduced consumption of energy, impact on energy prices, reduced VAT, etc. (European Commission, 2003) The strongest effects are seen in the area of semi-skilled labour in the building trades, which also accounts for the strongest regional policy effects. Furthermore, the European Commission (2005) estimates that a 20% saving on present energy consumption in the European Union by 2020 has the potential to create, directly or indirectly, up to one million new jobs in Europe.

Meyer and Lutz (2002) use the COMPASS model to study the carbon taxes for the G7 countries. They find that recycling revenues via social security contributions increases employment by nearly 1% by 2010 in France and Germany, but much less in US and Japan. Bach *et al.* (2002), using the models PANTHA RHEI and LEAN, find that the modest ecological tax reform enacted in Germany in 1999–2003 increased employment by 0.1 to 0.6% by 2010. This is as much as 250,000 additional jobs. There is also a 2–2.5% reduction in CO_2 emissions and a negligible effect on GDP. The labour intensity of renewable energy sources has been estimated to be approximately 10 times higher in Poland than that of traditional coal power (0.1–0.9 jobs/GWh compared to 0.01–0.1 jobs/GWh). Given this assumption, government targets for renewable energy would create 30,000 new jobs by 2010 (Jeeninga *et al.*, 1999).

In a study of climate policies for California, Hanemann *et al.* (2006) report small increases in employment for a package of measures focusing on the tightening of regulations affecting emissions.

11.8.3 Impacts of GHG mitigation on energy security

Since the TAR, new literature has addressed the question of energy security and climate change, especially following the rapid increases and fluctuations in commodity prices, particularly oil, in the period 2004-2006. The concept of energy security is usually understood to be an issue of the reliability of energy supplies that is illustrated by the exposure of oil im-porters to world market prices (Bauen, 2006) and, as Sullivan and Blyth (2006) point out, the reliability of electricity systems given the growing penetration of intermittant renewables, which may require back-up generation capacity (but see UKERC, 2006).

The possibilities of synergies and trade-offs between mitigation actions and energy security are very specific to national circumstances, particularly the relevant fuel mixes as a result of evolving energy markets, the sectors being targeted and energy consumption trends (Turton and Barreto, 2006). The transportation sector, in particular, is characterized by strong synergies relating to energy supply: measures replacing oil with domestic biofuels reduce both emissions and reliance on oil imports. Mitigation action for the electricity sector may lead to synergies with energy security. For example, a more decentralized system based on new renewable generation may reduce gas imports. Alternatively, there may be trade-offs. For example, security reasons may lead countries to increase their dependence on internal reserves of coal rather than relying on natural gas imports (Kuik, 2003).

Whether in the form of synergies or trade-offs, there is a growing recognition of the critical linkages that exist between climate change and energy security, and the fact that energy prices still have yet to reflect these 'externalities' effectively (Bauen, 2006). The inability to manage either one of these threats could result in significant economic and social costs (Turton and Barreto, 2006). Measures that successfully address both issues therefore have the potential to provide signficant social and economic benefits. In conclusion, it seems likely that climate change and energy security pressures will become more acute as international development proceeds. Public policies to address either of these issues can take many forms and their combination makes the effects uncertain, implying a gap in understanding their synergies and trade-offs (Blyth and Lefevre, 2004).

11.8.4 Summary

The recent literature has produced an increasing understanding of the interactions between greenhouse gas mitigation and other policy areas. Numerous studies have identified a wide range of co-benefits and quantified them for industrialized and developing countries. However, the literature does not (as yet) provide a complete picture that includes all the different types of co-benefits needed for a comprehensive assessment. Nevertheless, even the co-benefits quantified at present can make up substantial fractions of, or under specific conditions even exceed, direct mitigation costs.

Beyond the recognition of co-benefits, the realization of potential synergies and avoidance of trade-offs requires an integrated approach that considers a single set of technologies or policy measures in order to simultaneously address all relevant areas. There are practical examples of targeted programmes for pinpointing co-benefits and identifying those policy measures that offer most potential for capturing possible synergies.

In the case of low-income countries, the consideration of potential synergies between GHG mitigation and other policy objectives could be even more important than in high-income countries. At present, climate change policies are often still relatively marginal issues in these countries compared to issues such as poverty eradication, food supply, the provision of energy services, employment, transportation and local environmental quality. Accelerated and sustainable development could therefore become a common interest for both local and global communities (Criqui *et al.*, 2003).

11.9 Mitigation and adaptation - synergies and trade-offs

This section brings together the effects of climate change on mitigation action and the effects of mitigation action on adaptation as identified in Chapters 4 to 10 above. The topic of adaptation-mitigation linkage is covered in Chapter 2, Section 6, and IPCC (2007b, Chapter 18), which is the main reference for concepts, definitions, and analyses. The issue of adaptation-mitigation linkages, particularly when exploring synergies, is fairly nascent in the published literature: Barker (2003) and Dessai and Hulme (2003) analyze mitigation and adaptation linkages as fairly distinctive responses within the context of integrated assessment models; while Dang *et al.* (2003) and Klein *et al.* (2003) have more explicitly addressed the issue of whether and how mitigation and adaptation measures could be more effectively integrated as an overall response to the threat of climate change. Tol (2005) argues that adaptation and mitigation are policy substitutes and should be analyzed as an integrated response to climate change. However, they are usually addressed in different policy and institutional contexts, and policies are implemented at different spatial and temporal scales. This hampers analysis and weakens the trade-offs between adaptation and mitigation. An exception is facilitative adaptation (enhancing adaptive capacity). Like mitigation, it requires long-term policies at the macro-level, but they also compete for resources.

At the national level, mitigation and adaptation are often cast as competing priorities for policy makers (Cohen *et al.*, 1998; Michaelowa, 2001). In other words, interest groups will fight about the limited funds available in a country for addressing climate change, providing analyses of how countries might then make optimal decisions about the appropriate adaptation-mitigation 'mix'. Using a public choice model, Michaelowa (2001) finds that mitigation will be preferred by societies with a strong climate protection industry and low mitigation costs. Public pressure for adaptation will depend on the occurrence of extreme weather events. As technical adaptation measures will lead to benefits for closely-knit, clearly defined groups who can organize themselves well in the political process, these will benefit from subsidy-financed programmes. Changes in society will become less attractive as benefits are spread more widely.

Nonetheless, at the local level, there is a growing recognition that there are in fact important overlaps, particularly when natural, energy and sequestration systems intersect. Examples include bioenergy, forestry and agriculture (Morlot and Agrawala, 2004). This recognition is thought to be particularly relevant for developing countries, particularly the least developed countries, which rely extensively on natural resources for their energy and development needs. More specifically, there is a growing literature analyzing opportunities for linking adaptation and mitigation in agroforestry systems (Verchot, 2004; Verchot *et al.*, 2005), in forestry and agriculture (Dang *et al.*, 2003), and in coastal systems (Ehler *et al.*, 1997).

11.9.1 Sectoral mitigation action: links to climate change and adaptation

11.9.1.1 Energy

Section 4.5.5 covers the impact of climate change on energy supply, such as extreme events (Easterling *et al.*, 2000), the effect of warming on infrastructure (such as damage to gas and oil pipelines caused by permafrost melt) and changes in water levels for hydro projects (Nelson *et al.*, 2002). There is a broad consensus that a decentralized energy system (4.3.8) might be more robust in coping with extreme events. Areas that clearly link mitigation and adaptation include, in particular, hydro, biomass and nuclear. Changes in rainfall patterns/glacier melting will clearly impact hydro power and future hydro as a feasible carbon-neutral alternative. The same could be said for biomass, in which too much land used for energy crops may affect both food supply and forestry cover, thereby reducing the ability of communities to adapt to the impacts of climate change, reducing food supplies and therefore making them more vulnerable. Nuclear power generation has been vulnerable to shortages of cooling water due to heat-waves resulting in high ambient temperatures, like those in the EU in 2003 and 2006. This problem is expected to intensify with the rise in these climate-related events. There are opportunities for synergies between mitigation and adaptation in the area of energy supply, particularly for rural populations. For example, the opportunity to develop perennial biomass, such as switch grass, would meet rural energy needs and also provide adaptation benefits because of its relatively low water supply requirements (Samson *et al.*, 2000).

11.9.1.2 Transportation

Options for mitigation in transportation are not considered to be vulnerable to climate change. For transport there are no obvious links between mitigation and adaptation. Any adaptation of the system to climate change, e.g. more air conditioning in vehicles, is not expected to have a significant long-term impact on mitigation.

11.9.1.3 Commercial and residential buildings

While it is clear that the impact of climate change on commercial and residential buildings could be massive, particularly as a result of extreme events and sea level rises, there is less appreciation of the major synergies that are possible between adaptation and mitigation. Modern architecture rarely takes the prevailing climate into consideration, even though design options could result in a considerable reduction in the energy load of buildings, and improve their adaptation to a changing climate (Larsson, 2003). Nevertheless, there is a relatively small amount of literature exploring adaptation-mitigation linkages for new and existing buildings. One example is cool-roof technology options for adapting to higher temperatures. These options also provide mitigation advantages by reducing electricity use and CO_2 emissions. At the same time, cool roofs contribute to reducing the formation of ground level ozone. An example of a conflict between adaptation and mitigation is the effect of a sizeable increase in heat-waves in urban centres. An increase of this kind could intensify pressure for the penetration of inefficient air conditioners, increasing power demand and CO_2 emissions, as was the case during the heat-wave of 1–14 August 2003 in Europe.

11.9.1.4 Industry

Synergies and conflicts between mitigation and adaptation in the industry sector are highly site-specific (see 7.8). It is assumed that large firms would not be as vulnerable to flood risks or weather extremes since they have access to more financial and technical resources. There appears to be no literature indicating explicitly how industry could design its manufacturing and operating processes in such a way that, by adapting to possible climate change events, it can also help to reduce GHG emissions associated with their operations. It is obvious, however, that reducing energy demand would be a good adaptive and mitigative strategy if power supply (from hydro power, for example) were at risk from climate change (Subak *et al.*, 2000). Reducing dependence on cooling water may also be a good adaptive strategy in some locations, but the impact on emissions is not clear.

11.9.1.5 Agriculture and forestry

Most of the literature relating to mitigation-adaptation linkages concerns the agriculture and forestry sectors. In particular, there is a growing awareness of the unique contribution that such synergies could provide for the rural poor, particularly in the least developed countries: many measures focusing on sustainable natural resource management policies could provide both significant adaptation and mitigation benefits, mostly in the form of sequestration activities (Gundimeda, 2004; Morlot and Agrawala, 2004; Murdiyarso *et al.*, 2004). Agriculture is, of course, extremely vulnerable to the impact of climate change, that affects all aspects related to crop land management, and particularly areas related to water management (see Sections 8.5 and 8.8). Low-tillage practices are an example of a win-win technology that reduces erosion and the use of fossil fuels. As discussed in the energy section, bioenergy can of course play a significant role in mitigating global GHG emissions, although the full lifecycle implications of bioenergy options, including effects on deforestation and agriculture, need to be taken into account.

In the forestry sector, policies and measures often take neither adaptation nor mitigation into account (Huq and Grubb, 2004). There is increasing recognition that forestry mitigation projects can often have significant adaptation benefits, particularly in the areas of forest conservation, afforestation and reforestation, biomass energy plantations, agro-forestry, and urban forestry. These projects provide shading, and reduce water evaporation and vulnerability to heat stress. And many adaptation projects in the forestry sector can involve mitigation benefits, including soil and water conservation, agroforestry and biodiversity conservation.

With regard to the increase of biomass energy plantations as a mitigation measure (see Section 11.3.1.4), there may be increased competition for land in many regions, with two crucial effects. First, increased pressure to cultivate what are currently non-agricultural areas may reduce the area available to natural ecosystems, increase fragmentation and restrain the natural adaptive capacity. Secondly, increasing land rents might make agronomically viable adaptation options unprofitable. An alternative view is that there is no shortage of land (Bot *et al.*, 2000; Moreira, 2006), but of investment in land. In this view, the remedy consists of revenues derived from the energy sector (through the CDM, for example), both to raise land productivity through carbon-sequestering soil improvement and to co-produce food or fibre with biomass residuals for conversion to bioenergy products (Greene *et al.*, 2004; Read, 2005; Faaij, 2006; Lehmann *et al.*, 2006; Verchot *et al.*, 2005). Recent studies suggest that technological progress in agriculture will outstrip population growth under a variety of SRES scenarios, leaving enough land for bioenergy cropping, in the most optimistic scenario, to meet all forecast demands for primary energy (Hoogwijk *et al.*, 2005).

Mitigation may have a positive effect on adaptation in agriculture, depending on the circumstances. Additional employment in rural areas will raise incomes and reduce migration. Well-designed CDM projects can reduce the use of traditional biomass as fuel (Gundimeda, 2004) and replace it with marketable renewable fuels, providing a double benefit. There may be also benefits from some mitigation measures for human health, increasing the overall adaptive capacity of the population and making it less vulnerable to specific climate impacts (Tol and Dowlatabadi, 2001).

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Appendix to Chapter 11

Technical description of the assessment of aggregate mitigation potentials from the sectoral literature

1. Methodology for adding up sectoral emission reduction potential

Adding up all the emission reduction potentials at the sectoral level reported in the sectoral chapters will result in double counting for part of the potential. To avoid this, two interactions have been taken into account in the assessment of the total mitigation potential in Chapter 11 (Table 11.3):

- The interaction between the reduction potential from electricity savings in buildings and industry on the one hand and measures in the electricity supply sector on the other (substitution by low-carbon electricity supply). This topic is discussed in this appendix.
- The interaction between the estimated supply and demand of biomass for energy purposes. This topic is covered in Section 1.3.1.4.

1.1. The electricity sector

The two main reduction options for electricity use are:

1) electricity savings in the industry and buildings sector, and
2) substitution in the power sector tending towards low-carbon electricity technologies.

The overall CO_2 emission reduction from the electricity savings in industry and buildings therefore depends on the fuel mix of the power supply and the penetration of low-carbon technologies in that supply.

The methodology chosen to prevent double counting is presented in Figure 11.A1 and described below, step by step.

Step 1: Baseline electricity consumption and emissions

In step 1, 2000–2030 projections were compiled for final electricity consumption, primary energy consumption for electricity production and GHG emissions from the fuels used. The final electricity consumption at the regional basis was taken from the World Energy Outlook 2004 (IEA, 2004).

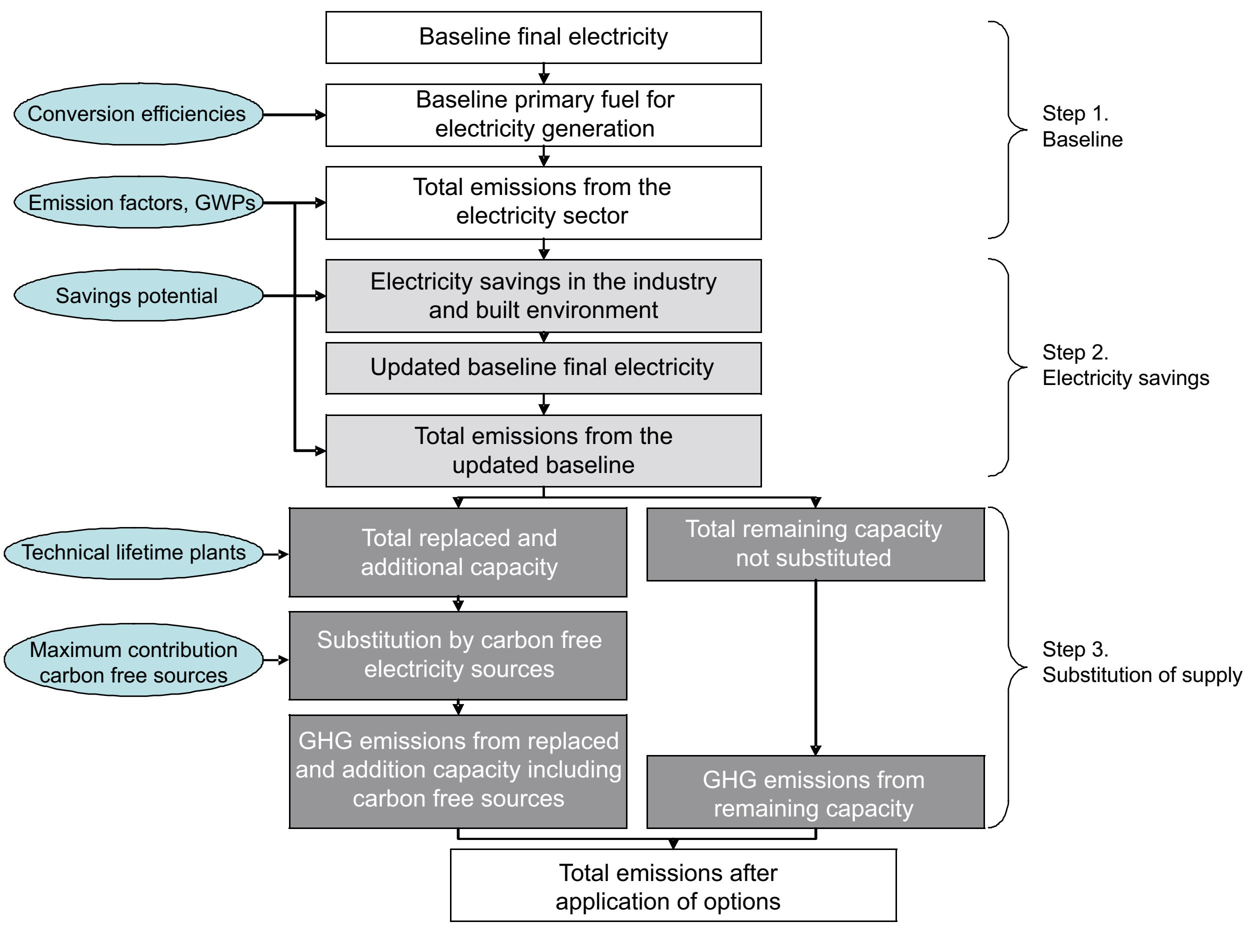

Figure 11.A1: *Methodology for the assessment of the mitigation potential related to electricity consumption; electricity savings and the implementation of low-carbon supply technologies*

To arrive at the primary fuel required for final electricity consumption, an intermediate step is needed. As the World Energy Outlook 2004 provides statistics on primary energy supply for electricity and heat combined, the implicit supplies required for heat were estimated and removed as follows. The primary energy consumption for electricity supply only was calculated on the basis of the efficiencies of combined heat and power, and a correction for the share of heat in total final energy consumption. The share of heat was calculated from the IEA Balances for the year 2002 and assumed to be constant over time. See also Section 4.4.3 for the efficiencies and the baseline in the year 2030.

Finally, using the data on primary fuel required, the GHG emissions were estimated on the basis of the primary fuel supply for power production using the emission factors for primary fuels (IEA, 2005) and the 1996 GWP numbers taken from UNFCCC.

Step 2: The electricity savings

The second step consists of reducing the baseline electricity by the savings from buildings and industry. Electricity savings are found at relatively low costs and they are therefore expected to be implemented first. The maximum electricity savings for the industry and buildings sector were taken from the sectoral chapters. These have been applied using the share of the electricity consumption of the sectors in total electricity consumption (WEO2004). In this step, it was assumed that the savings were equally distributed across the different power sources, including low-carbon sources.

The savings indicated in Table 11.A1 have been used.

In fact, it can be expected that electricity savings will result in higher levels of fossil-fuel electricity generation compared to generation at low marginal cost such as renewables and nuclear. This is because, in the usual operation of electricity systems, low-cost fuels are dispatched before high-cost fuels. But system operation depends on local conditions and it is not appropriate to consider these here. This consideration implies that the emission reductions for electricity savings reported here are underestimated. Higher carbon prices, and higher marginal costs of fossil fuels, exacerbate this effect.

Finally, the amount of primary fuels needed for power generation has been updated, resulting in lower emissions. The difference between the emissions from the updated baseline and the original baseline gives the avoided emissions; see Table 11.A2 (see also Section 11.3.3).

Step 3: The substitution of generating capacity with low-carbon capacity

The reduction in GHG emissions achieved through substitution towards low-carbon intensive technologies was assessed using the updated electricity demand from step 2.

First, an estimate of the new required generation capacity from 2010 to 2030 was made. It was assumed that low-carbon technologies are only implemented when new capacity is to be installed. The required new capacity to 2030 was calculated from 1) additional capacity between 2010 and 2030 to meet new demand and 2) capacity replaced in the period 2010–2030 after an assumed average plant lifetime of 50 years (see Chapter 4.4.3).

Secondly, the fuel switch from coal to natural gas was considered to be the option involving least cost, so it was assumed that it would be implemented first. Since new gas infrastructure is required, it was assumed in accordance with Chapter 4 that 20% at most of the new required coal plants (in the baseline) could be substituted by gas technologies.

Thirdly, after the fuel switch, emissions avoided from the other low-carbon substitution options were assessed. The following technologies were taken into account: renewables (such as wind, geothermal and solar), bioenergy, hydro, nuclear and CCS. It was assumed that the new fossil-fuel generation required according to the baseline was substituted by low-carbon generation (for each of the cost classes), proportional to the relative maximum technical potential of the technologies. The technologies were assumed to penetrate so as to achieve maximum shares in generation, as described in Table 4.20.

Finally, the new fossil fuel requirement was estimated and the GHG emissions assessed.

The avoided emissions in each of the steps were calculated using the same emission factors as in the baseline indicated above, and they are presented in Table 11.A2.

Table 11.A1: *Main assumptions used in the assessment of the emission reduction potential because of electricity savings in the buildings and industry sector*

	Assumption (%)	Origin
Electricity savings in the industrial sector	13[a]	Section 7.5.1
Electricity savings in the residential sector (mean value)		Section 6.5
OECD	23-26	
EIT	44-55	
Non-OECD	43-48	

Note:
[a] Chapter 7 reports energy savings of 30% compared to frozen efficiency for motor systems. Within the baseline, 10% efficiency improvements can be assumed. In addition, motors take about 65% of the total energy use resulting in electricity savings for 2030 of 13%.

Table 11.A2: *Baseline electricity demand and supply fuel mix with electricity savings (step 2) and mitigation measures in the power sector (step 3) in 2030*

	Baseline (1)			After electricity savings (2)			After substitution (3)			
	Primary energy (EJ)	Secondary energy (TWh)	Emissions ($GtCO_2$-eq)	Secondary energy (TWh)	Emissions ($GtCO_2$-eq)	Emissions avoided compared to 1 ($GtCO_2$-eq)	Secondary energy (TWh)	Emissions ($GtCO_2$-eq)	Emissions avoided compared to 2 ($GtCO_2$-eq)	Total emissions avoided ($MtCO_2$-eq)
OECD-EIT	**115**	**14244**	**6.0**	**11333**	**4.8**	**1.2**	**11333**	**3.1**	**1.7**	**2911**
Coal	42	4736	4.0	3768	3.2		2447	2.2		
Oil	3	309	0.21	246	0.17		246	0.17		
Gas	31	4145	1.8	3298	1.4		1689	0.73		
Nuclear	23	2137		1700			2653			
Hydro	5	1529		1217			1592			
Biomass and Waste	5	405		322			478			
Other Renewables	6	983		782			1274			
Coal - CCS							955			
EIT	**22**	**2468**	**1.2**	**1743**	**0.83**	**0.35**	**1743**	**0.55**	**0.27**	**594**
Coal	4	394	0.42	278	0.29		234	0.26		
Oil	1	61	0.06	43	0.04		42	0.04		
Gas	12	1324	0.70	935	0.49		480	0.25		
Nuclear	3	272		192			436			
Hydro	1	373		263			263			
Biomass and Waste	0	11		8			78			
Other Renewables	0	33		23			122			
Coal - CCS							87			
Non-OECD	**125**	**14944**	**8.6**	**10219**	**5.9**	**2.7**	**10219**	**3.2**	**2.7**	**5109**
Coal	66	6961	6.3	4760	4.3		2239	2.2		
Oil	8	812	0.59	555	0.4		410	0.3		
Gas	30	3860	1.7	2640	1.2		1644	0.74		
Nuclear	6	520		356			1022			
Hydro	8	2346		1604			2044			
Biomass and Waste	4	211		144			1022			
Other Renewables	3	234		160			920			
Coal - CCS							920			
Total	**263**	**31656**	**15.8**	**23295**	**11.5**	**4.3**	**23295**	**6.8**	**4.7**	**8613**

Table 11.A3: *The main results of the emission reductions for the sensitivity cases in $GtCO_2$-eq reduction*

	Default			Change in order[a)]			Lowest range	
	Savings		Low-carbon supply	Savings		Low-carbon supply	Savings	Low-carbon supply
	Buildings	Industry		Buildings	Industry			
OECD	0.9	0.3	1.7	0.06	0.03	2.7	1.2	0.9
EIT	0.3	0.1	0.27	0.02	0.02	0.49	0.35	0.18
Non-OECD/ EIT	2.3	0.5	2.7	0.25	0.18	4.1	2.7	1.3
Total	3.5	0.8	4.7	0.33	0.24	7.2	4.3	2.4

Note:
a) For the change in order, the maximum shares of low-carbon technologies were used (the default in Chapter 4)

1.2. Cost distribution

The sector chapters assessed the distribution of the total emission potentials across cost categories. The same cost distribution has been used to present the results in Table 11.3.

2. Sensitivity analysis for potentials in the electricity sector

A sensitivity analysis was carried out to analyse the robustness of the mitigation potential for the electricity sector. The following assumptions were varied:

1) The order of the mitigation option. Instead of assuming that electricity savings occurs before substitution with low-carbon technologies, the potential was also assessed in the reverse order: first substitution, then savings.
2) The value of the ‘maximum’ shares of low-carbon technologies in the total electricity mix. In Section 4.3 and 4.4 the results are presented for the ‘maximum’ shares based on various literature sources. Shares differ depending on the different technologies. To assess the sensitivity of these shares, they were varied in the lowest range by 30%, which is consistent with the lowest range in Chapter 4.

The results of each of the sensitivity analyses are presented in Table 11.A3.

Based on the sensitivity analysis it can be concluded that, when assuming the reverse order by allocating emission reductions first to the power sector, followed by the electricity savings, the total emission reduction, i.e. the aggregate of the electricity savings and substitution, would be 1.2 $GtCO_2$-eq lower than the default. This is a consequence of allocating the savings over the total electricity generation mix. The potential is equally sensitive to the ‘maximum’ shares that are assumed. Reducing these maximum shares by 30% reduces the mitigation potential of the power sector by 50% compared to the default.