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|---|---|---|
| Title: | Mitigation from a cross-sectoral perspective | |
| Chapter: | 11 | |
| (Sub)Section: | all | |
| Author(s): | CLAs: | Terry Barker (UK) and Igor Bashmakov (Russia) |
| | LAs: | Awwad Alharthi (Saudi Arabia), Markus Amann (Austria), Luis Cifuentes (Chile), Maosheng Duan (China), John Drexhage (Canada), Brian Flannery (USA), Michael Grubb (UK), Francis I. Ibitoye (Nigeria), Catrinus J. Jepma (Netherlands), William A. Pizer (USA), Stefan P. Schleicher (Austria), Kenji Yamaji (Japan) |
| | CAs: | Lenny Bernstein (USA), Shimon Awerbuch, Hitoshi Hayami (Japan), Tom Heggedal, Snorre Kverndokk, John Latham, Axel Michealowa (Germany), David Popp, Peter Read, Mike Smith, Ferenc Toth |
| | REs: | Aviel Verbruggen (Belgium), David Hawkins (USA) |
| Remarks: | | |
| File name: | Ch11_SOD_200706_MV-PB-RD_SB21h22.doc | |
| Date: | 20/07/06 | Time-zone: CET |

# Chapter 11 Mitigation from a cross-sectoral perspective

# EXECUTIVE SUMMARY

*Introduction*
This chapter summarises the sectoral estimates of the economic potentials and costs of mitigation covered in Chapters 4 to 10 and extends them to allow for interactions between sectors and technologies and unconventional technologies. It provides a comparison between the bottom-up and top-down estimates and an assessment of the shorter-term implications of long-term stabilization scenarios covered in Chapter 3. It provides an assessment of the macroeconomic costs, spillovers and co-benefits of action.

*Options for Mitigation*
A wide range of mitigation options is available, some at net benefit (no regrets) using market costs, especially those involving methane capture. Options in the main sectors are summarised from Chapters 4 to 10 by cost range, scale and uncertainty. The summary is complicated by interactions and the magnitude of spillover impacts with other policies, across sectors, over time, over regions, boundary definitions, and markets. System-wide approaches are more comprehensive summaries of aggregate potential, and can include the effects of common technologies (sensors, management systems, etc.).

*Unconventional Options*
Geo-engineering options to remove $CO_2$ directly from the air e.g. by ocean fertilization, or to block sunlight, remain largely speculative, uncosted and with potential for unknown side-effects. Blocking sunlight does not affect the expected escalation in atmospheric $CO_2$ levels, but could reduce or eliminate the associated warming. This disconnection of the link between $CO_2$ concentration and global temperature could have beneficial consequences, for example in increasing the productivity of agriculture and forestry, but there are also risks, e.g. further acidification of the oceans.

*Costs from Sectoral Energy-Engineering Studies*
The review of the mitigation potentials at different costs confirms the TAR finding of substantial opportunities at costs less than 20-27 US$/t$CO_2$ eq. As a rough estimate, a total potential in 2030 of about 4 Gt $CO_2$ eq is estimated at net benefits, with a large share in the building sector, and an additional potential of about 6 Gt $CO_2$ eq at additional costs of less than 20 US$/t$CO_2$ eq. These totals do not include transport and material efficiency improvements in industry. The total bottom-up potential at costs less than 20 US$/t$CO_2$ eq (10 Gt $CO_2$ eq) is also within the range suggested by the top-down models for these carbon prices by 2030. The potential at costs up to 100 US$/t$CO_2$ eq (18-25 Gt $CO_2$ eq) appears consistent with the few top-down estimates for much higher carbon prices by 2030.

It is very likely that no one sector or technology will be able to successfully address the mitigation challenge, suggesting a diversified portfolio based on a variety of criteria. A large part of the long term mitigation potential is found in the power and industry sectors. The bottom-up analysis for 2030 highlights the availability of a very significant potential in the building sector. Mitigation by agriculture is also important, with a share of about 18 % of the total at additional costs less than 20 US$/t$CO_2$ eq.

The gap with estimates of costs from top-down models has largely gone, partly because some of the top-down models have introduced more bottom-up features, especially experience curves incorporating learning-by doing. The results from hybrid modelling confirm that the costs arising tend to fall between those of purely top-down and bottom-up models - although the studies emphasise that the costs depend heavily upon the technology assumptions.

*Macroeconomic Costs of Mitigation under the Kyoto Protocol and post-2012*
Since the TAR, two trends have governed analysis of macroeconomic effects from climate change policy. One has been an evolution of events, ranging from the entry into force of the Kyoto Protocol without the United States and Australia, to a variety of domestic initiatives in different countries. Modelling efforts have addressed post-Kyoto strategies, and more intricate domestic policies. The second trend has been an evolution of models and modelling, with efforts to bridge existing gaps, particularly in the area of technological development, and explain differences among results. Both trends have led to refined estimates of climate policy costs, through more accurate representation of policy implementation, improved modelling technique, and improved understanding - meta analysis - of existing results.

In the longer term, achievable concentrations will be influenced by the timing and stability of carbon prices. Top-down assessments agree with the bottom-up results in suggesting that pathways of stable and predictable carbon prices to around 20-30 $US/tCO$_2$ eq (US$80-120/tC) by 2030 are sufficient to drive large-scale fuel switching and make both CCS and low-carbon power sources economic as the technologies mature. Incentives of this order might also play an important role in avoiding deforestation. Efficient pathways towards stabilization near 450ppm ($CO_2$ only) would require rising, stable and predictable global carbon prices exceeding such levels not later than 2030 and probably much earlier, and to continue rising later. Pathways towards 550ppm ($CO_2$ only) could be compatible with such prices being deferred until after 2030. Studies by the International Energy Agency suggest that a mid-range pathway, 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 with substantial investment in low-carbon energy technologies and supply.

Effects of the measures on GDP or GNP by 2030 vary accordingly. For the 550ppm $CO_2$ pathways and 20-30 $/tCO$_2$ prices, modelling studies suggest that gross world product would be at worst some 0.5% below baseline by 2030, depending on policy mix and incentives for innovation and deployment of low-carbon technologies. Effects for more stringent targets are more uncertain, with most studies suggesting costs less than 0.8% global output, with the estimates heavily dependent on approaches and assumptions.

*Technological Change, Diffusion and Deployment*
The literature makes a strong case on the need for ongoing innovation now to lower overall costs. All studies make clear the need for innovation to deliver currently non-commercial technologies in the long run for stabilization of greenhouse gas concentrations.

A major development since the TAR has been the inclusion in many top-down models of induced technological change. Using different approaches, modelling studies suggest that allowing for induced technological change may lead to substantial reductions in carbon tax rates and $CO_2$ permit prices as well as GDP costs, compared to those in the TAR in which technological change was largely assumed to be independent of mitigation policies and action. However, this finding is conditional upon first the assumption of cost-effective achievement of a given stabilisation target and second the characterisation of technological change as through learning-by-doing. If technological change is *also* assumed to come through increasing the stock of knowledge through R&D investment, then the reductions in costs would be much greater, although this remains speculative. Co-benefits of the actions in the form of reduced damages (e.g. less air pollution), more energy security or more rural employment, would further reduce costs.

However many top-down models are often very abstract with no technological detail and a stylised (if any) specification of spillover effects. Their empirical basis is very weak; they are highly deterministic and usually fail to account for the major uncertainties. Finally the models' treatment of policy instruments is very limited. They usually cover only one instrument, when there are two market failures involved (climate change damages and spillover benefits from investment), so that least two instruments should be included for policy assessment.

*Public Policy and Induced Technological Change*

One apparently robust conclusion from many reviews is the need for public policy to promote a broad portfolio of research both because results cannot be guaranteed and because governments have a poor track record when picking technical winners or losers. However some studies suggest that if policy is focused on R&D, then it may have negligible effect because the low-carbon R&D may crowd out other R&D. There are many potential areas for low-carbon R&D research (nuclear, renewables, carbon capture), and large-scale public investment in any of them risks substantial waste of resources if promised cost reductions do not materialise. However when market signals, through carbon taxes or cap and trade schemes are introduced, the markets will reward cost-effective technologies, through profitability and deployment. Even so, in some cases, the short-term market response may prevent adoption of more fruitful options in the longer term.

As regards portfolio analysis of government actions, a general finding is that that a portfolio of options that attempts to balance emission reductions across sectors in a manner that appears equitable (e.g. by equal percentage reduction), is likely to be more costly than an approach primarily guided by cost-efficiency. A second general finding is that costs will be reduced if options that correct the two market failures of climate-change-damages and technological-innovation-benefits are combined, e.g. by recycling revenues from permit auctions to support energy-efficiency and low-carbon innovations.

The common theme in all these studies is the need for multiple and mutually supporting policies that combine technology push and pull forces, across the various stages of the 'innovation chain', so as to foster more effective innovation and more rapid diffusion of low carbon technologies, nationally and internationally. Most also emphasise the need for feedbacks that enable policy to learn from experience and experimentation - utilising 'learning by doing' in the process of policy development itself.

*Spillover Effects from Annex I Action*

In the empirical analysis of energy-intensive industries, the simple indicator of carbon leakage is insufficient for policy making. The potential beneficial effect of technology transfer to developing countries arising from technological development brought about by Annex I action is substantial for energy-intensive industries, but has so far not been quantified in a reliable manner. As far as existing mitigation actions are concerned, the empirical evidence seems to indicate that competitive losses are not significant, confirming a finding in the TAR.

Perhaps one of the most important ways in which spillovers from mitigation action in one region affects the others is through its effect on world fossil-fuel 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 fossil-fuel producer's response, oil, gas or coal prices may fall, leading to loss of revenues by the producers, and lower costs of imports for the consumers. Nearly all modelling studies that have been reviewed show more pronounced adverse effects on oil-producing countries than on most of the Annex I countries who are taking the abatement measures.

*Co-benefits of Mitigation Action*

While the studies use different methodological approaches, there is general consensus for all analyzed world regions 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 technologies and sectors chosen. In developing countries, much of the health benefit could occur by improving the efficiency of or switching away from traditional use of coal and biomass. Such near-term secondary 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 turned out to be less than current projections shows

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 these 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. Thus, piecemeal regulatory treatment of individual pollutants rather than a comprehensive approach could lead to stranded investments in equipment.

*Adaptation and mitigation from a sectoral perspective*

The implications of some mitigation actions for adaptation dominate the scene, particularly renewable energy from land-based biomass, There is a growing awareness of the unique contribution that synergies between mitigation and adaptation could provide for the rural poor, particularly in least developed countries: many actions focusing on sustainable natural resource management policies could potentially provide both significant adaptation benefits while also working to provide mitigation benefits, mostly in the form of sequestration activities, that may not easily be measurable or verified.

## 11.1 Introduction

The UNFCCC (Article 3.3) states that "polices and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible costs." This chapter assesses the cross-sectoral literature on mitigation costs and potentials using different policies and measures both separately and in portfolios. It consolidates the estimates from this literature with those from Chapters 4 to 10 and compares and synthesises the results. Compared with Chapter 3, it adopts a more sectoral, and a more short and medium term perspective, taking the assessment to 2030 and 2050 but not beyond.

This report emphasizes the sectoral approach to mitigation. The effects of all government policies and measures - directly or indirectly - influence GHG emissions, and in principle these can be allocated by sector. There are many specific policies targeted to reduce GHG emissions (emissions/carbon/energy taxes, tradable permits, voluntary agreements, as discussed in Chapter 13 below). Non-specific policies may also yield substantial GHG reductions as ancillary benefits, as discussed in Section 11.8 below. All these policies have direct sectoral effects, but also indirect cross-sectoral effects, and these also diffuse across countries e.g. domestic policies reducing the energy use of domestic lighting lead to reductions in emissions of GHG from electricity generation and may lead to more exports of the new technology and potentially further energy saving abroad.

The main robust conclusions from the TAR on the macroeconomic and sectoral costs of mitigation can be summarised 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 of stabilization tend to rise as levels of atmospheric stabilization are reduced. Unplanned and unexpected policies with sudden short-term effects may cost much more for the same eventual results as 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. Effectiveness of adaptation and mitigation is increased and costs reduced if they are integrated with policies for sustainable development.

The main developments in the literature since 2000 can be summarised. (1) There is much more literature on the quantitative implications of introducing endogenous technological change into the models on their estimates of costs. Many studies suggest that higher social prices of carbon and other climate policies will accelerate the adoption of low-carbon technologies, and lower the costs with estimates ranging from a negligible amount to negative costs (net benefits). The long-term effects are discussed in Chapter 3 whereas section 11.5 below discusses the implications for the modelling and the shorter-term results. (2) Further reconciliation has been made of top-down and bottom-up estimates of potentials, and, significantly, more detailed identification of barriers and estimates of their effects on costs. (3) Multi-gas studies have been done on reductions in costs from mitigation of non-$CO_2$ GHGs, especially those such as methane from coal mines and waste tips that can be captured and put to economic use.

The global macroeconomic studies reviewed in this chapter consider the system costs of mitigation, albeit under various limiting assumptions, which affect the cost estimates. Some of these studies provide sectoral estimates of the costs and potentials consistently with the totals and these estimates implicitly include spillover effects arising through trade, prices or technology. However, the literature reviewed in Chapters 4 to 10, covering single sectors or regions, omits such spillover effects. A crucial problem for this synthesis chapter is how to add up these sectoral estimates of potentials and reconcile them with the global estimates, allowing for linkages and synergies between sectors and avoiding double counting of benefits or costs. Clearly the effects of some technologies cut across the sectors, such as the development of hydrogen use by the energy sector for transportation. This chapter compares the costs of these technologies, e.g. more energy efficiency versus more electricity from renewable sources.

The chapter starts with an overview of the 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, such as ocean fertilization, cloud creation and bio- and geo-engineering. Section 11.3. covers overall mitigation potential by sector, bringing together the various options and presenting the assessment of the sectoral implications of mitigation comparing bottom-up with top-down estimates. Section 11.4 covers the literature on the macroeconomic costs of mitigation. Section 11.5 describes the effect of introducing endogenous technological change into the models, particularly the effects of inducing technological change through climate policies. The remainder of the chapter treats interactions of various kinds: Section 11.6 relates the medium-term to the long-term issues discussed in Chapter 3, linking the shorter term (to 2050) costs and social prices of carbon with the longer-term stabilization targets; 11.7 covers spillovers from action in one group of countries on the rest; 11.8 covers co-benefits (particularly local air quality benefits) and costs; and 11.9 synergies and trade-offs between mitigation and adaptation.

## 11.2 Cross-Sectoral Mitigation Technological Options: Description and Characterization

This section summarises the technologies from Chapters 4 to 10 of Part 2 of the Report, reviews technologies that cut across sectors, such as those of the hydrogen economy, and extends the assessment to geo-engineering and other options not covered in Part 2.

### *11.2.1 Technological Options for Mitigation*

#### 11.2.1.1 Differences between Individual Sectors and Cross-Sectoral Policies

Policies and measures seldom have similar impact on the various sectors of an economy. Even relatively generic policy measures such as energy/carbon taxes or emissions trading schemes simultaneously implemented on a wide range of sectors, will have different implications depending on sector-specific supply and demand conditions, the availability of substitutes, learning aspects, etc. Other policies and measures are typically designed for specific sectors only, e.g. only for transport, power production or waste management, and will therefore by definition have an unequal impact across sectors. Table 11.1 categorises a large set of policies and measures to show whether their main impact is inherently sector-specific or generic across several sectors.

***Table 11.1:*** *Generic and sector-specific policies and measures*

| | | Generic* | Sector specific** | Exceptions possible*** |
|---|---|---|---|---|
| | Market based instruments | | | |
| 1 | (Harmonized/international) taxes on emissions | | | x |
| 2 | (Harmonized/international) taxes on energy | | | x |
| 3 | Tradable permits/quotas | | | x |
| 4 | subsidies | | x | |
| 5 | Deposit-refund systems | | x | |
| 6 | Domestic emissions trading | | | x |
| 7 | Kyoto mechanisms | x | | |
| | International emissions trading (IET) | x | | |
| | Joint Implementation (JI) | x | | |
| | Clean Development Mechanism (CDM) | x | | |
| | Regulatory instruments | | | |
| 8 | Non-tradable permits/quotas | | x | |
| 9 | (International) technology and product performance standards | | x | |
| | Energy-efficiency standards | | x | |
| 10 | Product bans | | x | |
| 11 | Direct government spending and investment (R&D | | x | |

| | | | | |
|---|---|---|---|---|
| | expenditures) | | | |
| | Information instruments | | | |
| 12 | Environmental labelling | | x | |
| 13 | Energy audits | | | x |
| 14 | Industrial reporting requirements | | x | |
| 15 | Information campaigns | x | | |
| 16 | DSM | x | | |
| 17 | (International) voluntary agreements (VA) | | x | |

* In principle implemented in all sectors
** In principle sector specific
*** Sector specific exemptions relatively easily implementable.

### 11.2.1.2 Linkage with Chapters 4-10

This section covers technologies that affect many sectors (11.2.2) and other technologies that cannot be attributed to any of the sectors covered in Chapters 4 to 10 (geo-engineering options etc in 11.2.3). The detailed consolidation and synthesis of the mitigation potentials and costs provided in Chapters 4 to 10 is covered in the next section, 11.3.

### *11.2.2 Cross-sectoral Technological Options*

Cross-sectoral mitigation technologies can be considered in three categories, those in which the implementation of the technology:

1. occurs in parallel in more than one sectors,
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 building sector, e.g. efficient HVAC system (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 6.4.10). 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 of 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, which has the potential to reduce building energy consumption (Section 6.4.5.4). IT is also key to the performance of hybrids and other advanced vehicle technologies (Section 5.4.2.1). Smart end-use devices (household appliances, etc) could use IT to program their operation to times when electricity demand was low. This would reduce peak demand for electricity, shifting more 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 a shift 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.

An example of a group of technologies that could involve interaction between sectors is gasification/hydrogen/carbon dioxide capture and storage (CCS) technology. While these technologies can be discussed separately, they are interrelated and their ability to mitigate $CO_2$ emissions is enhanced by their being applied as a group. 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 (IPCC, 2005). Using a pre-combustion approach, i.e., gasifying fossil fuels to produce hydrogen that can be used in fuel cells, offers the potential to improve overall energy efficiency. However, unless CCS is used to mitigate the $CO_2$ byproduct from this process, the use of that hydrogen will offer only modest benefits. (See Section 5.4.2.1 for a comparison of fuel cell and hybrid vehicles.) Adding CCS would make this a low $CO_2$ emission approach for use in transportation, building, or industrial applications.

Longer term, hydrogen could be manufactured by gasification of biomass, which has the potential for create negative $CO_2$ emissions (IPCC, 2005), or by electrolysis using carbon-free sources of electricity, a zero $CO_2$ option. Still longer-term, it may be possible to produce hydrogen by other processes, e.g. biologically, using genetically-modified organisms (GCEP, 2004). However, none of these longer-term technologies are likely to have a significant impact before 2030, the timeframe for this analysis.

Not all of the technology needed to implement this system is commercially available. An assessment conducted for the U.S. Department of Energy on fuel cell vehicle designs concluded that the cost of a vehicle fuel cell system was \$145/kWh (TIAX LLC, 2004) against a target price of \$30/kWh to be competitive with internal combustion engines (U.S. DOE, n.d.a). There are also unresolved safety problems associated with the widespread distribution of hydrogen that would be necessary to use fuel cells for either vehicles or in the buildings sector (U.S. DOE, n.d.b). However, \$145/kWh is well below the \$400-750/kWh that DOE estimates would be competitive for fuels cells in stationary source applications (U.S. DOE, n.d.a). Fuel cell systems have yet to demonstrate the 40,000 hours of reliable operation that DOE estimates would be necessary for these applications. Implementation of the fuel cells in stationary applications could provide valuable learning for vehicle application and could also be the basis for the hydrogen production and CCS implementation that would be needed use by other sectors.

Biomass is an example of a cross-sectoral technology in which there is the potential for competition for resources. Section 4.5.3 indicates that even the most optimistic estimates of global sustainable biomass potential would be insufficient to supply the projected world energy demand. Any assessment of the use of biomass, e.g., as a source of transportation fuels, needs to consider competing demands from other sectors for the biomass resource.

Natural gas availability could also 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.

### *11.2.3 Ocean Fertilization and Other Geo-engineering Options*

There is a risk that the conventional mitigation options will not be sufficient to achieve atmospheric stabilization. Since the TAR, a literature has developed on alternative, geo-engineering techniques for mitigating climate change. This section focuses on techniques which appear to offer promise: ocean fertilization, capturing and safely sequestering $CO_2$ and reducing the amount of sunlight absorbed by the earth-atmosphere system.

#### 11.2.3.1 Iron fertilization of the oceans

Iron fertilization of the oceans offers a potential strategy for removing $CO_2$ from the atmosphere by stimulating the growth of phytoplankton and thereby sequestering the $CO_2$ in the form of particulate organic carbon (POC). Several pilot experiments have clearly demonstrated the stimulated growth of marine biomass by the relatively low cost addition of iron salts to the ocean (Buesseler and Boyd, 2003) but, as yet, have provided little evidence for the transport of POC to the deep ocean. Further experiments are required to evaluate the scientific viability of this strategy. There have been 11 field studies in different oceanic regions with the primary aim of examining the impact of iron as a limiting nutrient of phytoplankton growth by addition of small quantities (1-10 tonnes) of iron sulphate to the surface ocean. Deliberate carbon sequestration has not been the driver behind these studies. 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 the ~30% of the oceans (the Southern Ocean, Equatorial Pacific and Sub-Arctic Pacific) that is iron-deplete. The second phase, of sinking and vertical transport of the increased phytoplankton biomass to depths below the main thermocline (>120m), has only been reported in two experiments to date. The efficiency of sequestration of the phytoplankton carbon is low (<10%), with the biomass being largely recycled back to $CO_2$ (Boyd *et al.*, 2004). This suggests that current estimates of carbon sequestered per unit iron (and per dollar) are over-estimates. The cost of large-scale and long-term fertilisation will also be offset by $CO_2$ release/emission during acquisition, transportation and release of large volumes of iron in remote oceanic regions. Potential negative impacts of iron fertilisation include 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 impacts have been directly identified in experiments to date, largely due to the time and space constraints.

#### 11.2.3.2 Other geo-engineering options for $CO_2$ capture and sequestration

Elliott *et al.*(2001) and Lackner (2002) have proposed thermodynamically viable schemes for removing $CO_2$ from the atmosphere prior to sequestration. In the future, direct injection of $CO_2$ into the ocean accelerates a natural process and could offer a possible further sequestration option (Herzog *et al.*, 2001). The gas would remain liquid below about 500m and is negatively buoyant below about 3000m. Furthermore, $CO_2$ hydrates can form at depths greater than 500m and, since they are denser than seawater water would tend to sink to the ocean bottom. The authors state that this would be economic but no details are given, and the costs would be above those for conventional sequestration. However, concerns regarding the impact of increased ocean acidity upon marine organisms have been expressed, which are relevant both to natural and artificial increases in oceanic $CO_2$ levels. The option of ocean storage and its ecological impacts are still in the research phase (IPCC, 2005).

#### 11.2.3.3 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 projected (2100) $CO_2$ levels this corresponds to a reduction of about 2%. Three techniques are considered.

- *A. Deflector System at Earth-Sun L-1[1] point.* The principle of this idea (e.g. Seifritz (1989), Teller *et al.* (2004)) is to install a barrier to sunlight - of area about $10^6$ $km^2$ - at or close to the L-1 point. Teller *et al.* estimate that its mass would be about 3000 t, consisting of a 30μm[2] metallic screen with 25nm[3] ribs. They envisage it being spun in situ, emplaced by 1 shuttle-flight per year over 100 years. It should have essentially zero maintenance. The cost is currently indeterminate. Computations by Govindasamy *et al.* (2003) suggest that this scheme could markedly diminish regional and seasonal climate change.
- *B. Stratospheric Reflecting Aerosols.* This technique involves controlled scattering of incoming sunlight by airborne sub-microscopic particles, which 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. Implications of these schemes, particularly with regard to stratospheric chemistry, require examination.
- *C. Albedo Enhancement of Atmospheric Clouds.* This scheme (Latham, 1990; Latham, 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 concentration in the clouds, increases their albedos for incoming sunlight, thus producing a cooling which could be controlled and (Jones *et al.*, 2005) (Bower *et al.)* sufficient to compensate for global warming. The required seawater atomization rate is about 10 $m^3$ /sec. The costs would be substantially less than for Scheme B. An advantage is that the only raw material required is seawater but, while the physics of this process are reasonably well-understood, its 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. This disconnection of the link between $CO_2$ concentration and global temperature could have beneficial consequences, for example in increasing the productivity of agriculture and forestry, but there are also risks, e.g. in acidification of the oceans.

## 11.3 Overall Mitigation Potential and Costs, including Portfolio Analysis and Cross-sectoral Modelling

The evaluation of the overall effects of the various technological and institutional mitigation options in different sectors requires a systematic investigation of the interactions across sectors. This section reviews the literature investigating such cross-sectoral effects to identify current knowledge on the integrated mitigation potential and /or costs covering more than two sectors. Studies relating to a portfolio analysis of mitigation options are also covered.

The first step of reviewing literatures is to identify the sectors where mitigation options interact. In Chapters 4-10, mitigation options are reviewed in the sectors of energy, transport,

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[1] This is the L1 Lagrange point between the sun and the earth.

[2] μm stands for micro millimeter (see glossary).

[3] Nm stands for nano millimetre (see glossary).

residential/commercial, industry, agriculture, forestry, and waste management. Since energy-related $CO_2$ emissions are the largest source of the greenhouse gases, it is helpful to organize a discussion of the interactions into energy supply-side and energy demand-side issues. There are many strong interactions between the options in the demand and supply of energy. There are the economic interactions such as the energy price effect on energy demand in different sectors, the effect of the load profile on the optimal generation mix, as well as many technological interactions. The effects identified by sector-wise studies could be enhanced or cancelled out depending on the system effects of demand-supply interactions.

Mitigation options in the sectors are related not only through the energy market but also through non-energy material flows, e.g., the choice of car design may cause the change of material production (and so GHG emissions) as well as fuel requirements. Mitigation options for GHGs other than energy-related $CO_2$ also have interactions across sectors, e.g., large-scale development of bioenergy will have effects on agriculture, forestry, energy supply and energy demand in all end-use sectors.

This section continues with a summary of the mitigation potentials provided in Chapters 4-10 and a review of the literature on cross-sectoral studies of low-cost potentials.

### *11.3.1 Integrated Summary of Sectoral Emission Potentials*

In the literature on economic potential[4] of mitigation, estimates differ depending on

- the modelling approach and various assumptions used (*e.g.* with regard to (1) the options to introduce new (carbon) price and non-price mitigation incentives, (2) technology development, or (3) the potential to lift barriers to effective action)
- the sector coverage
- the baseline used
- whether or not any impact of climate change itself was considered or
- any other (net) benefits, such as reductions in local air pollution.

In addition estimates of mitigation potential vary in terms of sector, region/country coverage and timescale of the projections. Despite the wide variety of specific or more general estimates of the economic mitigation potential, the policy relevant question addresses itself, *i.e.* whether the collective information from the literature allows for at least some crude but broadly acceptable estimates of the future mitigation potential (compared to some baseline estimate) for some predefined year, for some broad world regions and the world aggregate, and for some 'incentive regimes' (approximated by $/$tCO_2$ eq. carbon price to allow for possible comparable future incentive schemes).

This section derives some broad economic potentials, both for GHG mitigation for the world aggregate, and to the extent feasible, for the three main world regions, OECD (-EIT), EIT, Non-

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[4] For a distinction between the various concepts of mitigation potential, see Chapter 2. The definition of economic potential used is derived from the Guidance document on Costs & Potentials: "economic potential is cost-effective GHG mitigation when non-market costs and benefits are included with market costs and benefits in assessing the options for particular levels of carbon prices and when using social discount rates instead of private ones".

OECD, for the year 2030, and for 'incentive regimes' (expressed in $/tCO$_2$ eq. social unit cost of carbon), ranging from $<0-20, $<0-50, $<0-100, and $<0->100 at year 2000 prices.

In trying to put together such estimates, there are a number of challenges.
*Compatibility of results from different modelling approaches.* Two categories of fundamentally distinct modelling approaches for assessing the future mitigation potential can be distinguished in the literature (although various hybrid models combining the two approaches have been developed, since the TAR): bottom up (BU) and top-down (TD) models (for an overview of their differences, see 11.3.5 below). The important question arises as to whether the two modelling approaches converge in estimating economic potential. The estimates from the BU-TD literature will therefore be compared to analyse commonalities and differences, but this requires that the BU estimates be aggregated.

*Aggregation of results from various modelling activities.* The primary approach chosen in assessing the overall BU mitigation potential is to aggregate sector-specific estimates for all relevant sectors[5]. This is not satisfactory, because estimates throughout the literature are seldom based on identical and therefore completely comparable assumptions and approaches (the *'comparability issue'*). It also requires two further issues to be addressed:

- whether all sectors can be considered as jointly representing a complete picture of the economy (the *'coverage issue'*)
- whether there are aggregation biases that may either lead to over- or under-estimating the total aggregate (the *'aggregation issue'*).

It is fair to report at the outset that the three issues - the 'comparability issue', the 'coverage issue', and the 'aggregation issue' - cannot be completely resolved. However, if they are addressed as carefully as possible, acceptable estimates can be made from the BU literature, based on the judgements of the sectoral chapter authors, which can be used to compare with the TD estimates from the literature reviewed in Chapter 3 and Section 11.4, which follows.

#### 11.3.1.1 The 'comparability issue'

For some sectors, economic potentials have been based on the assumption that during the period to 2030 a fairly general mix of price and non-price based policies and measures are gradually implemented, which support the lifting of barriers to technological diffusion and deployment. Income distribution and development of financial institutions are as important as prices. For other sectors, the estimates of the mitigation potential are instead based on clearly defined price incentives (measured in $/tCO$_2$), whereas still other sector estimates are defined in terms of the impact of different levels of social costs (i.e. cost including non-market costs and benefits). Discount rates used in determining annualized net benefits of particular options may also vary between different estimates - although mostly country/region-specific social discount rates have been used. Other differences include the level of detail of underlying data, the coverage of any rebound effects, or the baseline used (e.g. both SRES and WEO). Moreover, for some sectors the mitigation potential has been estimated by confronting a constructed *ex-ante* input-based sector-specific cost curve with some monetized incentive (*e.g.* a hypothetical carbon tax or its equivalent, based on a broader mix

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[5] In addition some aggregate BU potential estimates based on regional instead of sectoral aggregation will be provided to check on aggregation consistency.

of price- and non-price based policies and measures). For other sectors the reverse approach was followed by introducing some mitigation potential and assessing *ex post* the implicit costs per tonne $CO_2$.

In short, due to the absence of the systematic implementation of a common standardized approach for assessing the mitigation potential in the underlying literature, the comparability of data has been far from perfect. However, by implementing a common reporting format to the extent feasible (as shown below), and acknowledging that any aberrations due to a lack of a common methodological base may in part cancel each other out in the aggregation process, the final result can be considered the best that can be done.

#### 11.3.1.2 The 'coverage issue'

Mitigation covers GHG emissions and sequestration from energy and non-energy use. It can be achieved throughout the chain of the energy cycle: from the exploration stage, through the transport and conversion stage into the end-use stage (see the discussion below on the aggregation of potentials over the various stages). The sectors considered in the BU-assessment cover all stages: most sector data are not completely linked to only one part of the energy chain, which may lead to attribution problems that need to be solved without losing consistency. There are, however, clear sector emphases on:
- mainly energy-supply-oriented sector activities: the energy supply and conversion sector;
- the use of energy in production: the agriculture, forestry, waste, transport, and industrial sector activities; and
- energy end-use: the residential and commercial activities in the built environment sector.

Jointly, the sector coverage is assumed to represent all mitigation potential throughout the energy cycle plus potential from non-energy sources and sinks in industry, agriculture and forestry. Possibly only a few economic activities have been disregarded in this set of sectors, *e.g.* where energy efficiency is achieved in end-use outdoor activity such as tourism or other leisure-related activities. The impact of any such omissions is expected to be very limited.

Another aspect is to which extent the data per sector cover all relevant sector activities. In transport, for instance, only the mitigation potential for light duty vehicles (LDV) has been assessed. Because LDV represents roughly two-third of transportation by road, and because road transportation represents roughly three-quarter of overall transport (air, water, and rail transport represent roughly 11, 9 and 3 percent of overall transport), the estimate broadly reflects half of the transport activity. To arrive at a full transport sector estimate, in the absence of other data, some crude extrapolation is required for overall coverage. For some other sectors and timeframes, the coverage issue was also solved by extrapolation (*e.g.* in the residential sector where the 2020 potential had been estimated, when that for 2030 was required).

#### 11.3.1.3 The 'aggregation issue'

The issue whether the mitigation potential estimates derived for separate sector activities can be aggregated to get to the overall potential estimate is rather complex, because mitigation action in one sector may affect the mitigation potential in other sectors positively or negatively. A clear example of a positive impact relates to cross-sectoral technology development: if for instance some smart ICT device is implemented in various industrial processes, saving considerable amounts of energy, then such device may probably be also - through the usual transfer of knowledge chains - become implemented in other sectors. If sector potential were only considered in isolation, such positive inter-linkages would be disregarded and lead to aggregation bias, whereby the overall potential would be *underestimated*. In the literature there are no systematic estimates of the size of this bias (for some considerations on cross-sectoral technologies, however, see section 11.2.2).

It is equally possible that mitigation action in one sector has a negative impact on the potential in another sector. A typical example of such a phenomenon is where end-use efficiencies are achieved, *e.g.* less energy is used for heating of housing, while at the same time, thanks to mitigation action in the energy production process, the primary energy mix has been changed (*e.g.* leading to less emissions per unit of energy), such that the emissions associated with the end-use energy savings may be less than if the primary energy mix had not changed. The overall potential derived from a mere sector aggregation would therefore cause such overall potential to be *overestimated*. Obviously the impact of a changing primary fuel mix on the mitigation impact of increasing end-use efficiencies does not have to lead to a risk of overestimating the overall potential: this all will depend on how the emission patterns associated with the fuel mix have changed.

Another issue is to determine what part of the primary energy production becomes redundant (or, in any case is no longer required) as end-use efficiencies increase or decentralised systems expand. If for instance 20% less energy would be needed for heating the residential sector, this will affect energy-production-related emissions. The calculation may assume that the most outdated and possibly least efficient and most polluting production units will be closed down, or, instead, it may use the national/regional average emissions in energy production, or possibly still another alternative, *e.g.* where one also takes international energy flows or extending lifetimes of existing capacity, into account. There is no universal rule for establishing a baseline for comparison in this regard; at the same time it is clear that the choice of such a baseline may have a serious impact on the aggregation bias.
Because there is no reason to assume *a priori* that the positive and negative sector interlinkages as described will cancel each other out, a number of studies (see 11.3.2.5 below) try to make corrections for at least any potential bias that may occur due to the interaction between mitigation results in end-use on the one hand and in energy supply on the other hand.

#### 11.3.1.4 The baseline

In principle it was decided to use the SRES B2 marker scenario as the baseline scenario for estimating the BU mitigation potential, although other baselines have also been used (*e.g.* WEO (2004) for energy production). One important feature of this baseline is that it assumes substantially lower energy prices than those in later projections (WEO, 2005 and 2006), based on the 2002-6 rises in world energy price, which 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/bbl, is comparable to the impact of a $100t/$CO_2$ eq. extra cost of carbon. However, it is still uncertain if 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 due to, for instance, economies of scale, the introduction of some new technologies may be much easier if already supported by a higher 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 in e.g. electricity generation, increasing GHG emissions.

### 11.3.1.5 A synthesis of mitigation potentials from Chapters 4 to 10

**Table 11.2** The origin and type of linkages of the power sector with other sectors included in AR4.

| | Demand side | Supply side | Competition |
|---|---|---|---|
| | | | |
| Transport | | | Both sectors use bioenergy and any overlap in consumption must be removed |
| Buildings | The electricity savings need to be removed from the power sector and the fuel mix for power adjusted. | | |
| Industry | The electricity savings need to be removed from the power sector and the fuel mix for power adjusted. | | |
| Agriculture | | Some of the potential for bioenergy supply is estimated in this chapter | |
| Forestry | | Some of the potential for bioenergy supply is estimated in this chapter | |
| Waste | | Potentials here include waste incineration and LFG recovery | |

As discussed above in order to avoid double counting in aggregating the sector potentials, the interlinkages between sectors need to be considered and allowed for. The power sector has most linkages and interactions with other sectors, as can be seen in Table 11.2. In estimating the estimates of mitigation potential for the power sector, a hierarchy in mitigation options has been defined using following steps:

1) The World Energy Outlook (IEA, 2004) for the year 2030 has been used as the baseline (Price *et al.*, 2006)

2) It was assumed that the estimates of potential mitigation from electricity savings in the built environment and the industry sector lead to a lower demand for electricity and a revised mix of generation technologies. Electricity savings were assumed to be allocated equally over the revised power mix.

3) The lower required capacity was divided into additional new capacity since 2010 and old capacity replaced after an average plant lifetime of 50 years linearly distributed.

4) Of the new power mix after electricity savings, it was assumed that the maximum share of renewable energy sources was implemented as introduced in Chapter 4. The intermittent renewable electricity was assumed to reduce generation from fossil fuels.
5) The remaining capacity was assumed to be substituted by either bioenergy, nuclear or carbon capture and storage (CCS) from coal or gas according to their maximum share in the electricity supply as indicated in Chapter 4. However, it was assumed that these sources can only substitute new capacity from the year 2010 onwards, with the first CCS plant operational after 2015, once new technologies had matured. Bioenergy and nuclear will probably be used earlier but CCS is implemented later on a larger scale.

Using this hierarchy, it implies that for all substitution technologies individually (intermittent, biomass, nuclear and CCS) lower mitigation potentials are found compared to the figures before applying the hierarchy (see Chapter 4). Choosing a different hierarchy will result in different individual results, although the total will not change significantly.

**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** (in brackets 2030 emissions WEO/SRES B2 scenario) | **Mitigation option** | **Region** | **Economic potential < 100 US\$/tCO$_2$eq** | | **Economic potential at different cost categories in US\$/tCO$_2$eq** | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Low | High | <0 | 0 - 20 | 20 - 50 | 50 - 100 |
| | | | Mton CO$_2$eq | | | | | |
| **Energy supply** (n.a.) | All options in energy supply excluding electricity savings in other sectors | OECD | 200 | 1400 | 100 | 200 | 290 | 200 |
| | | EIT | 300 | 500 | 60 | 80 | 150 | 150 |
| | | Non OECD | 1700 | 3100 | 700 | 700 | 1000 | - |
| | | Global | 2200 | 5100 | 850 | 1000 | 1400 | 350 |
| **Transport** (10.6 GtCO$_2$-CO$_2$ only) | Total | OECD | 1700 | | | | | |
| | | EIT | 150 | | | | | |
| | | Non OECD | 1100 | | | | | |
| | | Global | 3000 | | | | | |
| **Buildings** (15.0 GtCO$_2$-CO$_2$ only) | Electricity savings | OECD | 750 | | 750 | - | - | - |
| | | EIT | 100 | | 100 | - | - | - |
| | | Non OECD | 1200 | | 1200 | 20 | - | 20 |
| | | | | | | | | |
| | Fuel savings | OECD | 950 | 1000 | 750 | 100 | 150 | - |
| | | EIT | 500 | 550 | 300 | 250 | 10 | - |
| | | Non OECD | 150 | 500 | 250 | 100 | - | - |
| | | | | | | | | |
| | Total | OECD | 1700 | 1700 | 1500 | 100 | 150 | - |
| | | EIT | 600 | 700 | 400 | 250 | 10 | - |
| | | Non OECD | 1400 | 1700 | 1400 | 100 | - | 20 |
| | | Global | 3700 | 4100 | 3200 | 450 | 150 | 20 |
| **Industry** (13.4 GtCO$_2$-CO$_2$ only; 1 GtCO$_2$eq non-CO$_2$ emissions in 2020) | Electricity savings | OECD | 400 | | 100 | | 100 | 200 |
| | | EIT | 100 | | 30 | | 30 | 50 |
| | | Non OECD | 900 | | 200 | | 200 | 450 |
| | | | | | | | | |
| | Other savings, including non-CO$_2$ GHG | OECD | 300 | 900 | 300 | | 200 | 50 |
| | | EIT | 150 | 400 | 80 | | 200 | 20 |
| | | Non OECD | 900 | 2900 | 550 | | 1300 | 70 |
| | | | | | | | | |
| | Total | OECD | 700 | 1300 | 400 | | 300 | 250 |
| | | EIT | 300 | 550 | 100 | | 250 | 80 |
| | | Non OECD | 1800 | 3800 | 750 | | 1500 | 500 |
| | | Global | 2800 | 5600 | 1300 | | 2100 | 850 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Agriculture** (7.2 $GtCO_2eq$ in 2020) | | OECD | 800 | | | 450 | 150 | 250 |
| | | EIT | 150 | | | 50 | 50 | 80 |
| | | Non OECD | 2300 | | | 1600 | 250 | 500 |
| | | Global | 3300 | | | 2100 | 450 | 850 |
| **Forestry** (n.a) | | OECD | 700 | | 10 | 150 | 300 | 250 |
| | | EIT | 150 | | 0 | 40 | 40 | 60 |
| | | Non OECD | 1900 | | 150 | 850 | 550 | 350 |
| | | Global | 2700 | | 150 | 1100 | 900 | 650 |
| **Waste** (1.5 $GtCO_2eq$) | | Global | 550 | 1300 | 700 | | 200 | |
| **All sectors** | | OECD | 5900 | 7700 | 1600 | 1300 | 1200 | 1000 |
| | | EIT | 1700 | 2200 | 450 | 550 | 450 | 350 |
| | | Non OECD | 10000 | 13800 | 2200 | 3900 | 3400 | 1300 |
| | | Global | 18200 | 25000 | 4200 | 6500 | 5200 | 2700 |

Notes: For the origin of the data, see text. Mitigation potentials for Buildings, Industry, Forestry, Agriculture and Waste compared to the SRES B2 baseline, for Energy and Transport compared to the WEO baseline. Mitigation options in energy supply, transport and buildings are for $CO_2$ only, due to limited availability of information on the other gases. When available the lowest and the highest range in mitigation potential is given. Potentials per cost category are based on the average of the high and low mitigation potential estimate. Mitigation options at costs >100 US$/$tCO_2$ are not included here, but are reported in the source chapters. Only the numbers for waste are cut off at 50 $/$tCO_2$. Results in the industry cost category <20 US$/$tCO_2$ are included in the 0-20 US$/$tCO_2$ category. Total figures include only the categories for which data were available, causing e.g. deviations between the sum of regions and the global total. The total potentials for all sectors per cost category thus exclude transport, for which no costs specification is available. The transport potential includes an unknown amount of mitigation potential with costs >100 US$/$tCO_2$. Because the literature on mitigation in buildings for some regions did not cover high cost options, the building sector has a number of missing values. Without the electricity savings in buildings and industry, the energy supply sector could mitigate more than indicated here (see Chapter 4 for details). Transport mitigation potentials include light duty vehicles, biofuels and aviation only. Industry is exclusive of material efficiency improvements, other than through recycling. Mitigation targeted at heating and cooling is included in the building and industry sector only; combined heat and power is not included. Agriculture and forestry potential estimates are based on long term experimental results under current climate conditions. Under moderate deviations in climate the mitigation estimate is considered quite robust. Behavioural change in end-use sectors is not included. As these are bottom-up technological estimates, effects of trade and leakage between regions are not accounted for.

Technical note: where currently only central values are given they will as far as possible be replaced by a range in the final version

Table 11.3 brings together the estimates for the economic potentials[6] for GHG mitigation from Chapters 4 to 10, following the procedures outlined above. The table shows the potentials by sector divided into those for OECD, Economies in Transition (EIT), the rest of the world, and the global total. For the *industry and buildings sector* the emissions are separated into fuel emission savings taken from the chapters' estimates and electricity emission savings using the electricity baseline as used in the power sector estimates (step 2 in the described hierarchy). For the *forestry sector*, the emission reductions reported in Table 9.9 were used, however the 15% bioenergy reduction was first extracted as this was already included in the power sector (Table 9.8). For the *other sectors*, the potentials reported in the chapters were used. For some chapters (agriculture and waste) only global total figures were reported and included, the others were divided into OECD, EIT and non-OECD regions. In all cases the B2 scenario or the World Energy Outlook (WEO) Reference scenario (IEA, 2004a) was used as the baseline. The final emissions of both scenarios are comparable. For energy-related emissions in 2030, the B2 scenario has an estimate of 37 $GtCO_2$ and the WEO 39 $GtCO_2$.

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[6] Economic potential is defined for particular levels of carbon prices (as affected by mitigation policies). These levels of carbon prices are the "social unit costs of GHG mitigation". This chapter generally uses the term "carbon prices" to refer to the unit cost assumptions.

Note, however, that the mitigation potentials reported here include all greenhouse gases and processes.

The unit cost estimates have been taken from the sectoral chapters. For the solar, wind and the substitution potential in the power sector, the costs were calculated based on electricity costs and a linear cost supply was assumed. For the transport sector no cost figures have been indicated. The other chapters use different cost categories. For the overall table, all cost categories are indicated and where possible aggregated. Based on the cost assumptions, it can be concluded that around 4 $GtCO_2$ could be reduced by 2030 at negative costs, additional to the baseline. Around an additional 6 $GtCO_2$ could be reduced at costs below 20 US\$/$tCO_2$.

### 11.3.1.6 Differences with the TAR

Table 11.4 compares the AR4 estimates for 2030 with those from the TAR for 2020. The updated estimates are significantly higher due to:

- the different timeframe, 2030 compared to 2020 in the TAR;
- inclusion of the forestry sector, which was not included in the TAR; and
- the greater range of economic potentials to 100 US\$/$tCO_2$, compared to less that 27.3 US\$/$tCO_2$ (US\$100/tC) in the TAR.

The last column shows the AR4 estimates for potentials less than 20 US\$/$tCO_2$, which are more comparable with those from the TAR. For most sectors the ranges appear compatible, but the estimates for industry have been revised downwards substantially. Overall, the estimated bottom-up economic potential has been revised downwards compared to that in the TAR, especially considering that the AR4 estimates allow for about 5 more years of technological change. For explanation of other salient differences between AR4 and TAR results, see the various notes in the preceding Chapters 4-10.

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

| | | TAR potential emissions reductions by 2020 a) | | AR4 potential by 2030 at costs < 100 US$/tCO$_2$ | | AR4 potential by 2030 at costs <20 US$/tCO$_2$ |
|---|---|---|---|---|---|---|
| | | MtCO$_2$ eq/y | | | | |
| | | LOW | HIGH | LOW | HIGH | |
| Buildings | CO$_2$ only | 3667 | 4033 | 3700 | 4100 | 3700 |
| Transport | CO$_2$ only | 1100 | 2567 | 2900 | 3200 | n.a. |
| Industry | CO$_2$ only | | | 2800 | 5600 | 1300 |
| * energy efficiency | | 2567 | 3300 | | | |
| * material efficiency | | 2200 | 2200 | | | |
| | non-CO$_2$ | 367 | 367 | | | |
| Agriculture | CO$_2$ only | | | | 3300 b) | 2000 |
| | non-CO$_2$ | 1283 | 2750 | | | |
| Waste | CH4 only | 733 | 733 | 540 | 1250 | 700 |
| Energy supply and conversions | | 1283 | 2567 | 2200 | 5100 | 1800 |
| Forestry | | | | | 2700 b) | 1200 |
| Total | | 13200 | 18517 | 18200 | 25000 | 11000 c) |

a) The TAR range excludes options with costs above US$27.3/tCO$_2$ (100/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.
b) Middle value
c) This is the sum of the potential reduction at negative costs and below US$20/tCO$_2$. See however notes to Table 11.3.

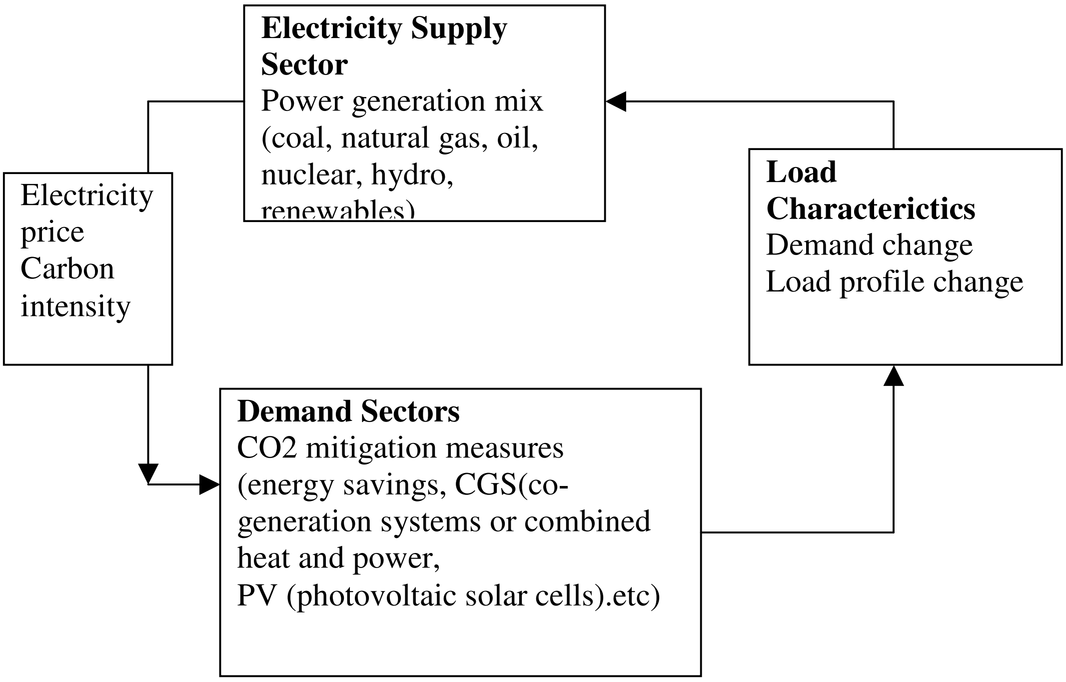
### *11.3.2 Studies on Energy Supply-Demand Interactions*

This section covers specific literature on energy demand-supply interactions, first considering 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.

#### 11.3.2.1 The Carbon Content of Electricity

As discussed above, there are many interactions between the CO$_2$ mitigation measures in the demand and supply of energy. Particularly, in case of electricity, considerations on the effects of interactions are important because final users cannot know the indirect carbon content of the electricity they use. Figure 11.1 illustrates the interactions of CO$_2$ mitigation measures in electricity supply- and demand- sectors.

**Figure 11.1**: Interactions of $CO_2$ mitigation measures in electricity supply- and demand- sectors



Iwafune *et al.* (2001a, b, c), 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 changing optimal mix in power generation reflecting changes in the load profile caused by the introductions of demand-side options such as 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 of Tokyo by 3.5% which reduces $CO_2$ emissions from power supply by 7.6%. The $CO_2$ emission intensity of the reduced electricity demand is more than two times larger 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”, between the average carbon intensity of electricity supply and the carbon value of electricity savings, is observed 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 effect of $CO_2$ emission reduction by introducing cogeneration (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 the $CO_2$ emissions from power generation. In a standard scenario where coal is the fuel used in incremental electricity demands, 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 very highly efficient CCGT (combined cycle gas turbine) is replaced by CHP. And, in the case where nuclear power is replaced by CHP, the total $CO_2$ emission from energy system conversely increases with CHP installation. These results suggest that the $CO_2$ reduction potential by the introduction of CHP should be evaluated with caution taking into consideration the future power plant construction program.

#### 11.3.2.2 The Effects of High Energy Prices on Mitigation

Price responses of energy demand can be much larger when energy prices are rising than when they are falling, whereas conventional *modelling* has symmetric responses. Thus the mitigation response to policy may be much larger when energy prices are rising. This phenomena is addressed in a literature on asymmetrical price responses and effects of technological change (Gately and Huntington, 2002; Griffin and Shulman, 2005). Bashmakov (2006) also argues for asymmetrical responses in analysis of what author calls the economics of constants and variables - the existence of very stable energy costs to income proportions, which may be observed for the long period of statistical observations in many countries. He argues that there are thresholds for total energy costs as a ratio of GDP or gross output, energy costs for transportation and for 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 brings different results depending on the relationship of the energy-costs to income or gross-output ratio to the threshold.

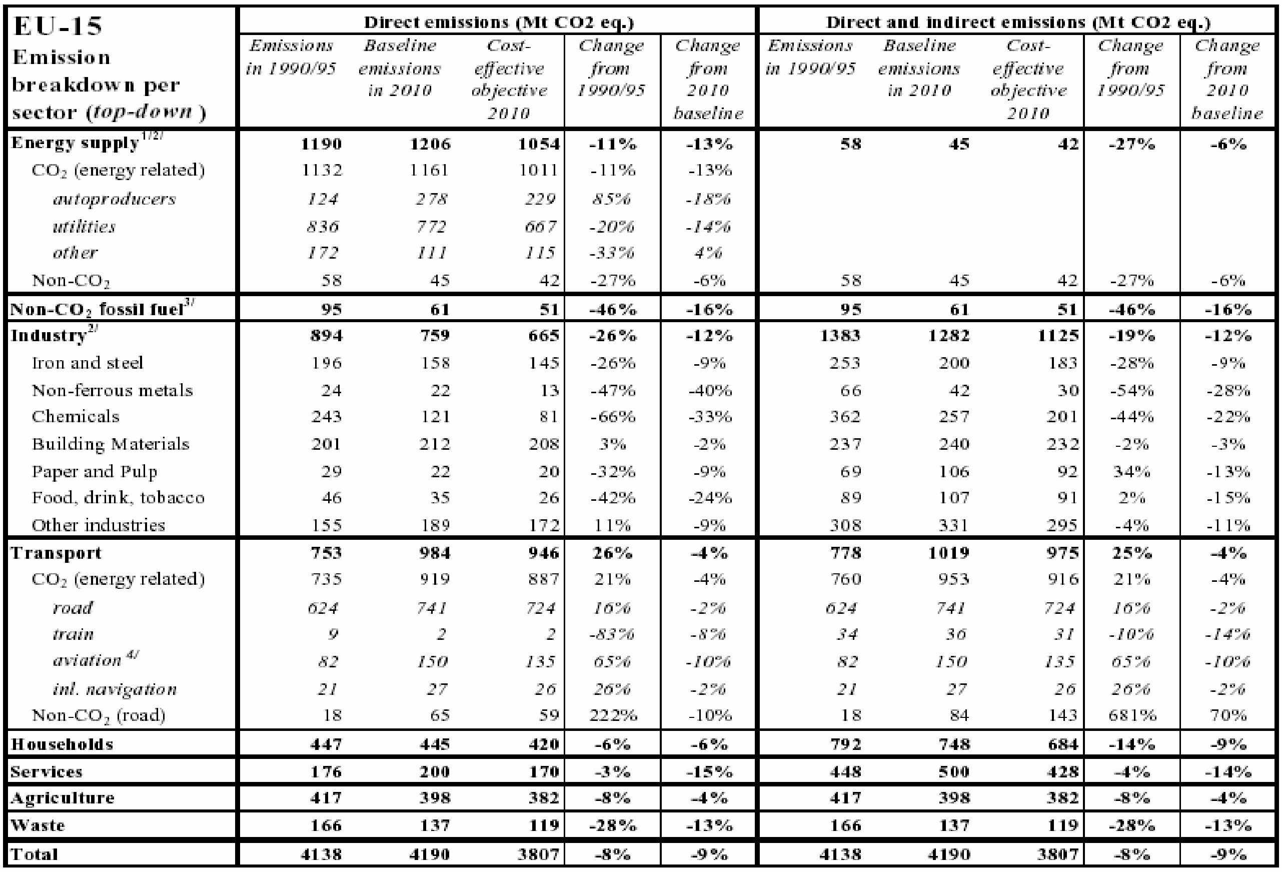
### *11.3.3 Cross-Sectoral Effects of Greenhouse Gas Mitigation Policies to 2025*

Various estimates of cross-sectoral mitigation potential have been published, usually as government-commissioned reports. 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 as a result literature on this topic is sparse.

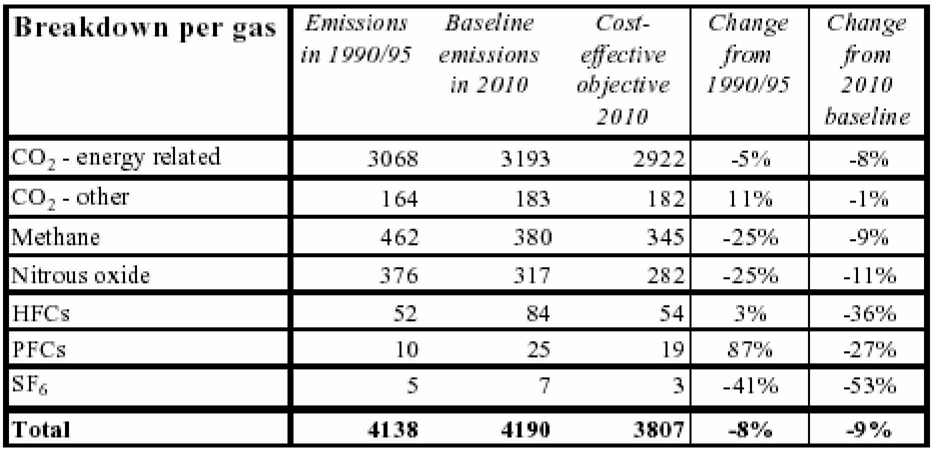
One major cross-sectoral study (EU DG Environment, 2001) brings together low-cost mitigation options and shows their effects across sectors and regions. It shows how a Kyoto-style target (8% reduction of EU GHGs below 1990/95 by 2010) can be achieved for the EU-15 Member States with options less than euro20/t$CO_2$, 1999 prices. The study assesses the direct and indirect outcomes using a top-down (PRIMES) for energy-related $CO_2$ and a bottom-up (GENESIS) model for all other GHGs, with the synthesis of the results presented in Table 11.5 below. This multigas 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 transport has an increase of 25% in relation to 1990/95 emissions. Note also the large reductions in methane and $N_2O$ in the achievement of the overall target as shown in the lower panel of the table. The results however are dominated by bottom-up energy-engineering assumptions, since PRIMES is a partial equilibrium model, so the GDP effects of the options is not provided.

*Table 11.5: Sectoral results from a meta-analysis of 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 (Mt CO2 eq.)** | | | | | **Direct and indirect emissions (Mt CO2 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**[1][2] | **1190** | **1206** | **1054** | **-11%** | **-13%** | **58** | **45** | **42** | **-27%** | **-6%** |
| $CO_2$ (energy related) | 1132 | 1161 | 1011 | -11% | -13% | | | | | |
| *autoproducers* | *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**[3] | **95** | **61** | **51** | **-46%** | **-16%** | **95** | **61** | **51** | **-46%** | **-16%** |
| **Industry**[2] | **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*[4] | *82* | *150* | *135* | *65%* | *-10%* | *82* | *150* | *135* | *65%* | *-10%* |
| *inl. 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% |
| $SF_6$ | 5 | 7 | 3 | -41% | -53% |
| **Total** | **4138** | **4190** | **3807** | **-8%** | **-9%** |

Notes:

1) The direct $CO_2$ emissions of energy supply are allocated to the energy demand sectors in the right part of the table representing direct and indirect emissions. Refineries are included in the energy supply sector.
2) Industrial boilers are allocated to industrial sectors.
3) Non-$CO_2$ GHG emissions from fossil fuel extraction, transport and distribution.
4) 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

There are also qualitative discussions of these effects in several submissions of the national communications of Annex I countries to the UNFCCC. The EU third national communication (2003), for example, reported a "with measures" scenario analysis that included policies already implemented by the EU-15 and some of those implemented by its member states, with the aim of establishing the most cost-effective emission reductions strategies in order to meet EU's commitment under Kyoto protocol. The 'with measures' projections show that by 2010 emissions would only increase by 1% relative to the base year; with "additional measures" the 2010 emissions could drop by 4.5% below the base year level. Similar qualitative treatment of cross-sectoral effects can be found in the most recent national communications of European member states, for example Norway (2002), Finland (2003) and United Kingdom (2003).

Meyer and Lutz (2002), using COMPASS, carried out a simulation to study the effects of carbon taxes for the group of G7 countries, which happen to be the most important energy users. For each of these countries the authors assumed that a carbon tax of 1US$ per ton of $CO_2$ is introduced in 2001, rising linearly to 10 US$ in 2010. Revenues arising from such taxes were assumed to be used to lower social security contributions. The effects on GDP and labour are summarized in top rows of Table 11.6. The table shows that a uniform tax rate of up to 10 US$/t $CO_2$ in 2010 induces varying effects in the G7 countries, e.g. GDP losses range from -1.72% for the US to -0.23% in Japan. Table 11.6 also shows effects on output: the decline in petroleum and coal products will be strongest, while on the other hand, the effects on construction will be mild.

*Table 11.6: Impact of a 1 US$/t$CO_2$ carbon tax introduced in 2001 and rising linearly to 10 US$/t$CO_2$ in 2010 on GDP, employment and sectoral output*
*(% difference from business-as-usual)*
Source: Meyer and Lutz (2002)

| | USA | Japan | Germany | France | Italy | Great Britain | Canada |
|---|---|---|---|---|---|---|---|
| GDP | -1.72 | -0.23 | -0.35 | -0.31 | -0.34 | -0.75 | -1.61 |
| Labour | 0.08 | 0.27 | 0.89 | 0.90 | 0.93 | 0.56 | 0.19 |
| Output: | | | | | | | |
| 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 |

Kainuma et al.(2004) examine the effects of carbon tax in Japan using the AIM (Asia-Pacific Integrated Model). Reported results show that if carbon tax is used as an instrument in order to meet the target of the Kyoto Protocol in the first commitment period, the average GDP loss will be 0.16% and a tax of 45,000 Japanese Yen/tC will be required. Under a tax and subsidy regime, the authors assume that carbon tax revenue will be utilized to subsidize $CO_2$ reduction countermeasures, and the levels of additional investments requirements are shown in Table 11.7 for each sector. The table shows that about 3,400 Japanese Yen/tC will be required as carbon tax in order to achieve the Kyoto Protocol, most of the investment will be in energy-saving measures. The average GDP loss relative to the baseline for tax plus subsidy regime is substantially lower (0.03%) compared to that with the carbon tax alone (0.16%).

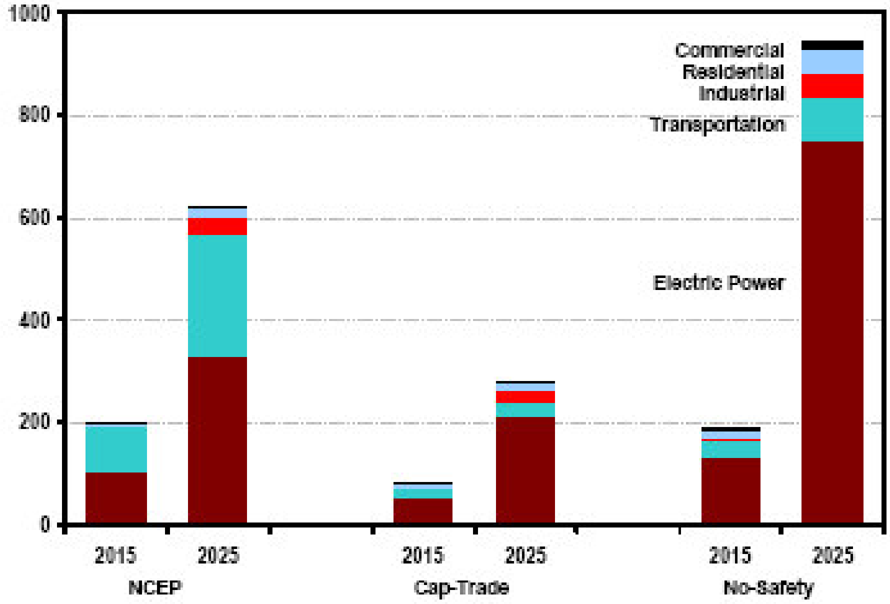
***Table 11.7:*** *Carbon tax rate and required additional investments for reducing $CO_2$ emissions in Japan.*
Source: Kainuma (2004)

| sector | Subsidized measures and devices | Additional investment (bil. JPY / year) |
|---|---|---|
| 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 | 101.3 |
| Residential sector | High efficiency air conditioner, High efficiency gas stove, Solar water heater, High efficiency gas cooking device, High efficiency television, High efficiency VTR, Latent heat recovery type water heater, High efficiency illuminator, High efficiency refrigerator, Standby electricity saving, Insulation | 353.9 |
| 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<br>lighting with timer, High efficiency vending machine, Amorphous transformer, Standby electricity saving, Heat pump, Insulation | 194.5 |
| Transportation sector | High efficiency gasoline private car, High efficiency diesel car, Hybrid commercial car, High efficiency diesel bus, High efficiency<br>small-sized truck, High efficiency standard-sized track | 106.6 |
| Forest management | Plantation, Weeding, tree thinning, multilayered thinning, Improvement of natural forest | 195.7 |
| Total | | 952.0 |
| Tax rate to appropriate required subsidiary payments (JPY/tC) | | 3,433 |

The US EIA (2005) has analysed the National Commission on Energy Policy's (NCEP) 2004 proposals involving 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/t$CO_2$ through to 2025) and a no-safety-valve case (in which the cost rises to \$US(2003)35/t$CO_2$ and the GHG reduction to 15% by 2025). The effects on $CO_2$ emissions by broad sector are shown in Figure 11.2. 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, hence the relatively large contributions of these sectors in this scenario. The cap-and-trade schemes have their main effects on the electricity sector, since the price of coal-fired generation rises relative to other generation technologies. The estimated cost of the NCEP scenario is 0.4% of the reference case GDP by 2025 and the overall growth of the economy is "not materially altered" (p. 42).

*Figure 11.2:_ 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.*
*Source: US Energy Information Administration (EIA)(2005, p.15)*

(Million Metric Tons)



### *11.3.4 Reconciling Top-down (TD) and Bottom-up (BU) Sectoral Potentials for 2030*

#### 11.3.4.1 Comparison of aggregate economic potentials from BU and TD modelling and analysis for 2030

In Table 11.8 brings together the BU estimates of economic potentials synthesized from Chapters 4 to 10, as discussed in 11.3.2, with the range of TD sectoral estimates presented in Chapter 3. The TD ranges for less than 20 US\$/tCO$_2$ are the highest and lowest estimates, sector by sector, for the models with carbon prices for this range, which covers 7 EMF21 multi-gas studies with prices varying widely between 2 and 29 US\$/tCO$_2$. The TD range for carbon prices less than 100 US\$/tCO$_2$ is simply the maximum of the two extra studies (using mini-Cam and IMAGE) in this range. The overall potentials are in overlapping ranges, illustrating a feature of the literature since the TAR, which shows that the BU and TD estimates are converging, partly as a result of the incorporation of BU components in the TD models. Calculations have also been done to aggregate the overall potentials from the IMCP studies, in which induced technological change further reduces costs (see 11.5 below). The maximum potential in each range is shown in the last line of the table. Evidently when technological change is allowed, the potentials are higher, and much higher for carbon prices approaching 100 US\$/tCO$_2$.

The emission reductions compare with projected global CO$_2$ emissions by 2030 of 39GtCO$_2$/yr in the World Energy Outlook, 2004, which forms the reference baseline for the energy sectoral estimates and for the IEA (2006) baseline; and about 37 GtCO2 in the SRES B2 scenario. The ‘bottom-up’ sectoral estimates thus represent 25-30% savings compared to baseline, at costs of under c. 20 US\$/tCO$_2$.

A number of points can be raised with regard to the comparison of BU and TD results.

1) The numbers are conditional upon particular TD carbon prices (shadow prices, tax rates and/or emission allowance prices) and they are not fixed at \$20 or \$50 or \$100 etc, so we have imputed potentials from a range of results from very different models.
2) GDP or grow world product costs are not always reported, but they are not necessarily closely correlated with the carbon tax rates or permit prices.
3) The TD results take into account the recent work on induced technological change and multi-gas stabilization - but the literature reports many different studies on different base-line, and the assumptions in the studies are critical in affecting the costs and prices. This is especially true of the outliers.

*Table 11.8: Economic potential for sectoral mitigation by 2030* $^{a)}$*: comparison of* bottom-up and top-down estimates (mtCO$_2$ eq)

| Chapter of this report | Sectors | <US\$20/tCO$_2$ eq central | <US\$20/tCO$_2$ eq | <US\$100/tCO$_2$ eq | <US\$100/tCO$_2$ eq maximum |
|---|---|---|---|---|---|
| | | Bottom-Up | Top-Down | Bottom-Up | Top-Down |
| 4 | Energy supply and conversion (including electricity savings) | 1800<br>(4200) $^{b)}$ | 566-8832 | 2200-5100<br>(5600 – 8500) $^{b)}$ | 15253 |
| 5 | Transport | Not available | 56-1318 | 3000 | 3328 |
| 6 | Buildings | 1700$^{c)}$ | 287-625 | 1600-2050 $^{c)}$ | 2080 |
| 7 | Industry | 900 $^{c)}$ | 475-1954 | 1400-4200 $^{c)}$ | 5492 |
| 8 | Agriculture | 2100 | -1012-1128 | 3300 | 915 |
| 9 | Forestry | 1200 | 0-1444 | 2700 | 704 |
| 10 | Waste | 700 | 0-896 | 550-1300 | 1186 |
| 11 | Total electricity savings | 2400 | | 3400 | |
| | Total adjusted for effects from energy sector | 82000 | 1875-15531 | 18000-25000 | 23848 |
| | IMCP potentials with induced technological change (9 models) | | 17000 | | 27200 |

Sources: Tables 3.16, 3.17 and 11.3 and Edenhofer et al., 2006
Notes:
a) For comparison, the level of GHG emissions for 2030 in the B2-MESSAGE scenario is 57801 MtCO2 eq (Table 3.17)
b) The figures in parentheses indicate the total electricity savings from both the building and the industry sector (see Table 11.3)
c) These figures exclude the electricity savings in these regions.
See notes to Tables 3.16, 3.17 and 11.3.3.

#### 11.3.4.2 Comparison of BU-TD sectoral patterns of emission savings

With the major exception around the role of building-related energy use, and allowing for differences in sourcing emissions between the TD and BU estimates, the TD potentials correspond to the BU sectoral pattern of mitigation costs and potentials derived from Chapters 4-10 (Table 11.8). Building energy use is in a separate category because the great majority of emission savings (around 3200 $MtCO_2$/yr) are estimated to be economically attractive without incurring any carbon cost: its realization is dependent mostly upon other policy measures, as discussed in the buildings chapter. If this can all be realized, it offers substantial potential. The sectoral chapter data also indicate that other energy efficiency measures, e.g. in industrial heat, also play an important role by 2030. This also corresponds with the findings of long-term national and international studies (e.g. Chapter 3, Table 3.10 and Figure 3.25), namely that early savings tend to arise particularly from energy efficiency.

The corresponding ‘negative cost’ potential in power generation is estimated at 800 MtCO2/yr globally. But both the sectoral evidence, and the top-down models, indicate that decarbonisation of power generation takes off at carbon prices in the range up to $20-25/tCO2 ($80-100/tC). Moreover, decarbonising power generation in many of these studies appears to be a necessary precursor to decarbonising the transport sector using advanced technologies like electric vehicles and the ‘hydrogen economy’: electrification of the transport sector, and often the use of fuel cells, only reduces emissions if the power sector itself is first low carbon. Moreover given limits on biofuel potentials, the overall costs of decarbonising transport are much more uncertain, particularly in respect of fuel substitution, and the associated technologies are less developed. Efficiency improvements in transport are important, but these various factors mean that decarbonisation of transport tends to lag behind power generation and probably requires higher carbon prices.

The sector studies of Chapters 4-10 suggest that, within the energy-related sectors, the additional emission reductions associated with the price range 0-20 US$/$tCO_2$ are dominated by savings in the power sector (1000 $MtCO_2$), compared to 450 $MtCO_2$ in buildings. All industry-related abatement below 20 US$/$tCO_2$ may amount to about 1200 $MtCO_2$ (not divided by cost class) of which about a third is associated with electricity savings. The sector-chapter-based data suggest the potential is also significant in the other sectors at costs below about 20 US$/$tCO_2$, at round 2000 $MtCO_2$/yr from agriculture, 1000 MtC/yr from forestry, and 700 $MtCO_2$/yr from improved waste management. The total abatement potential by 2030 of around 3000$MtCO_2$/yr in the transport sector does not attempt any cost categorization.

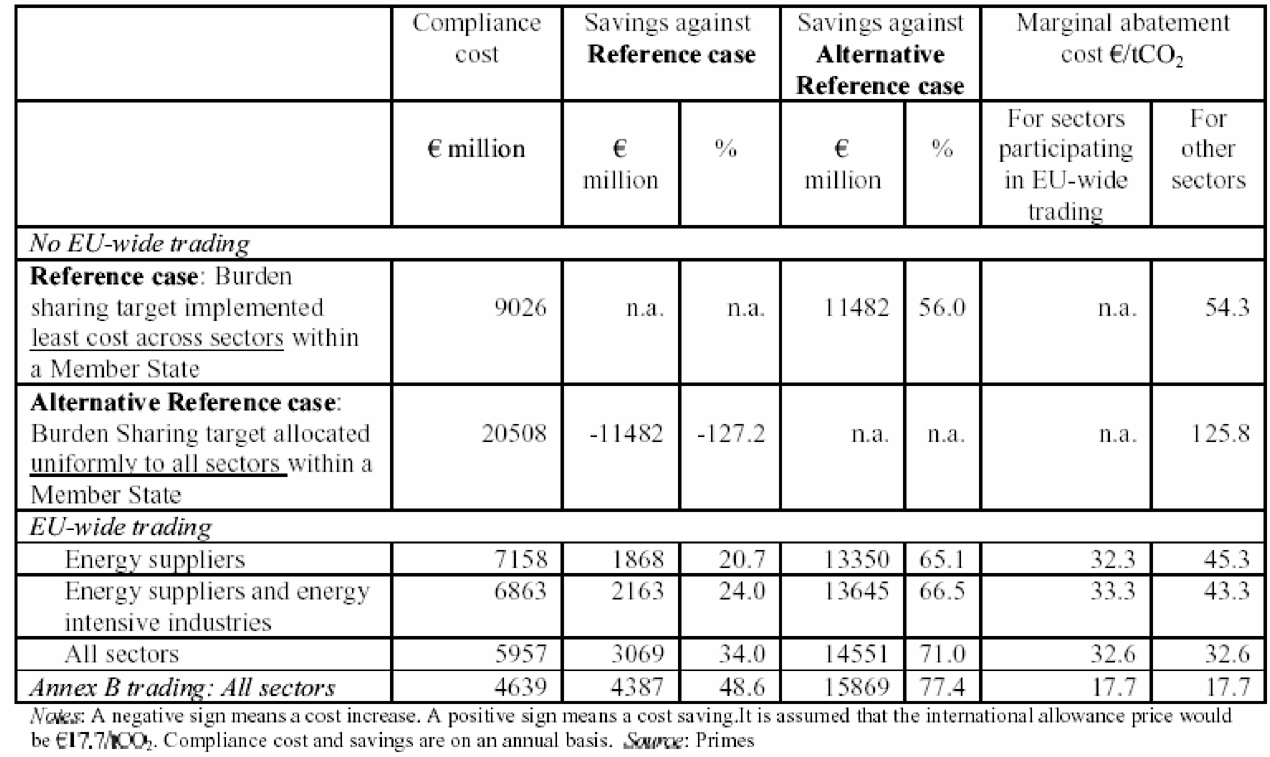
Closer analysis of the sectoral pattern of changes, sketched in detail in the 2006 IEA study but also evident in the other global modelling studies, reveals that the majority of emission savings in the early decades are associated with end-use savings and abatement in the energy and industry sectors, notably in electricity generation. Moreover, economies in mitigation scenarios tend to become more electrified (Edmonds *et al.*). This is particularly true with respect to the global economic models (other bottom-up considerations are discussed below). A major reason why carbon prices up to 100 US$/tC play a big role in the IEA scenario, and in the IMCP 450ppm$CO_2$ results, is because of their impact in the power sector: this, very roughly, is a price sufficient to lead to decarbonisation of the electricity system, through a mix of strategies including CCS and diverse other low carbon power sources, which are unlikely to be economic at much lower carbon prices. In the IEA study, the power sector by 2050 is over 50% non-fossil generation, and half of the remainder is coal plant with CCS. The power sector still tends to dominate emission savings by 2030 even at lesser carbon prices (e.g. Chapter 3, Table 3.16), but obviously the degree of decarbonisation is much less.

### *11.3.5 Portfolio Analysis of Mitigation Options*

Portfolio analysis is the study of the mix of actions available to policy makers to reduce emissions or adapt to climate change. There appears to be no literature that explicitly subjects mitigation options and actions to a portfolio analysis. However one important issue for governments is the allocation of the burden of GHG abatement across sectors or regions. It appears to be equitable to allocate the reductions equally across sectors, yet if the incremental costs are different an equal allocation can be very inefficient. Several studies have addressed this issue.

Capros and Mantos (2001) in a report for EU DG Environment show the value of emission trading in achieving more cost-effective mitigation in order to reach the Kyoto target. The important point is that equal reductions across sectors costs more than twice as much as an allocation based on least costs (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.

*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 €/tCO$_2$ | |
|---|---|---|---|---|---|---|---|
| | **€ million** | € million | % | € million | % | For sectors participating in EU-wide trading | For other sectors |
| *No EU-wide trading* | | | | | | | |
| **Reference case**: Burden sharing target implemented 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/tCO$_2$. Compliance cost and savings are on an annual basis. *Source*: Primes

*Notes: 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 in the economy, illustrating an allocation evidently more expensive than the least-cost one of the reference case.*
Source: Capros and Mantzos (2000, p8)

A related issue is the allocation of CO$_2$ emissions reductions under Kyoto to sources in the Emissions Trading Scheme (ETS) versus all non-ETS sources. Klepper and Peterson (2006) using a CGE model examine the implications of the current National Allocation Plans (NAP) as well as different assumptions about the use and availability of CDM and JI credits. There are strong distortions having the ETS exist parallel to other policy measures in the non-ETS sectors, such that the NAPs reduce the allowance price in the ETS below the implicit tax necessary for reaching the Kyoto targets in the non-ETS sectors. The limited use of CDM and JI in the current policies will have a welfare loss of close to 1% in 2012 relative to “business as usual”, but an unrestricted trading in project credits and allowances would result in an allocation where the Kyoto target can be met with hardly any welfare costs.

Jaccard *et al.* (2002) evaluate the cost of climate policy in Canada. They compare the costs of achieving Kyoto target in 2010 using CIMS model for sector or national targets. According to their estimates, the electricity, residential, and commercial/institutional sectors, with have relatively lower marginal costs, contribute more to reductions when sector targets are transformed into a national target, while the industry and transportation sectors contribute less. For example, the marginal cost for the electricity sector is 30 C$30/tCO2 eq for the sector target and 120 C$/tCO2 eq for the national target while those of industrial sector are 300 C$/$tCO_2$e and 120 C$/$tCO_2$ eq respectively. Correspondingly the GHG abatement cost for the electricity sector is C$(1995)15.71 bn for the sector target and C$(1995)28.47 bn, while those of industrial sector are 34.41 and 11.35 respectively. Both studies illustrate a general finding that a portfolio of options that attempts to balance emission reductions across sectors in a manner that appears fair or democratic, is likely to be more costly than an approach optimizing the policy mix for cost-effectiveness.

## 11.4 Macroeconomic Effects

In the TAR, the discussion of macroeconomic effects focused on the costs-mitigation expenditures, marginal abatement cost (allowance price in a trading scheme), changes in GDP, changes in welfare, and changes in employment-associated with various policies to reduce emissions. Since the TAR, there has been an evolution of events, ranging from the entry into force of the Kyoto Protocol without the United States and Australia, to a variety of domestic initiatives in different countries. This has led to a variety of modelling efforts addressing post-Kyoto strategies, on the one hand, and more intricate domestic policies on the other, providing more refined estimates of climate policy costs, through more accurate representation of policy implementation, improved modelling technique, and improved understanding-meta analysis-of existing results.

### *11.4.1 Models in Use and Measures of Economic Costs*

**Table 11.10:** Models discussed in section 11.5.

| | | |
|---|---|---|
| R&DICE | Nordhaus (2002) | Models R&D investment |
| | Goulder and Matthai (2000) | Models R&D investment or LBD |
| MIND | Edenhofer *et al.* (2005) | Endogenous growth; backstop technology |
| FEEM-RICE | Buonanno, P. *et al.* (2003) | Endogenous growth; backstop technology |
| ENTICE | Popp (2004) | Endogenous growth |
| AIM | Masui *et al.* (2005) | Bottom up |
| SGM | Edmonds *et al.* (2004) | |
| Worldscan | Riahi *et al.* (2004); Bollen *et al.* (2004) | CGE |
| MARIA | Mori and Saito (2004) | |
| MERGE | Manne and Richels (2004) | |
| IMAGE2.2 | Van Vuuren *et al.* (2004) | IAM linked to CGE |
| DNE21 | Akimoto *et al.* (2004) | |
| MARKAL | Smenkens-Ramierz Morales (2004) | Detailed energy demand model |
| EPPA | McFarland *et al.* (2004), Paltsev *et al*. (2003) | |
| NEMS | Energy Information Administration (various years) | Detailed energy demand model |
| PRIMES | Capros and Mantzos (2000) | Detailed energy model; partial equilibrium |
| POLES | IPTS (2000); Criqui and Kitous (2003) | Detailed energy model; partial equilibrium |
| GTEM | Viguier *et al*. (2003) | CGE |
| EDGE | Burniaux (2000) | |
| E3MG | Barker *et al.* (2006) | Econometric; demand-led |

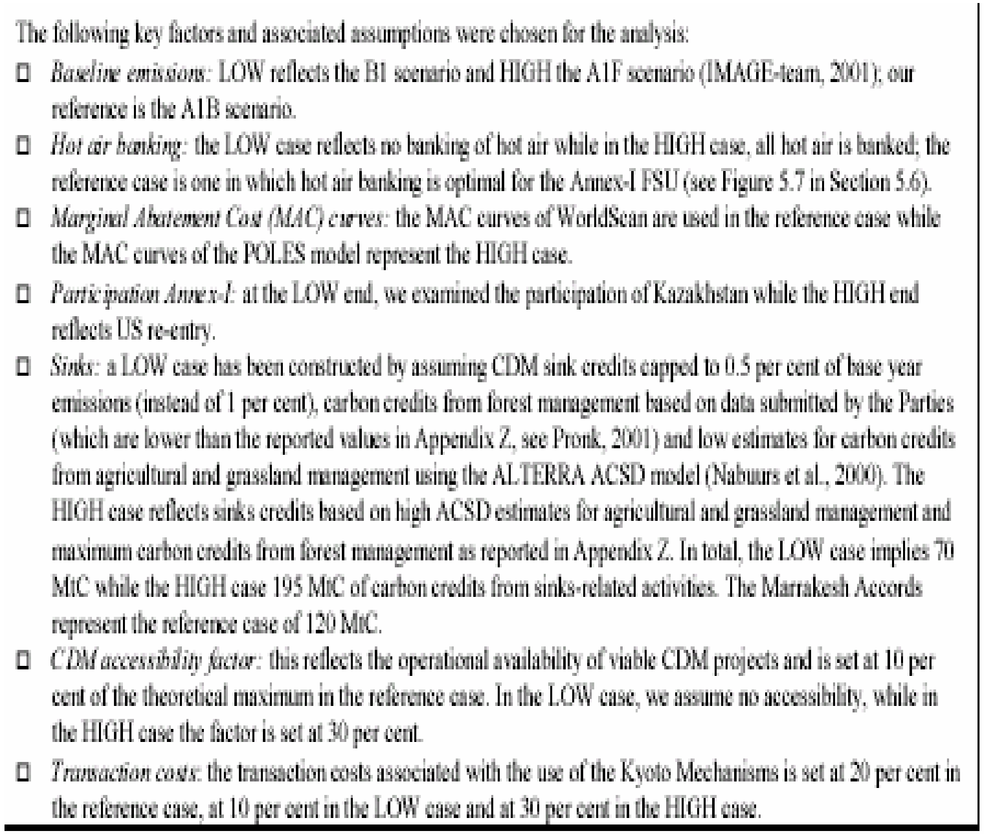
Table11.4.1 lists the models discussed in this chapter that have been used to estimate aggregate economic impacts of climate policies. Chapter 2 discusses cost concepts, and here we report, where available, the prices associated with $CO_2$ emissions, and the cost in terms of GDP, welfare and employment loss or gain.

The TAR reviewed studies of climate policy interactions with the existing tax system. Such interactions change the aggregate impacts 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 (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, as well as proposals in the U.S., Japan, and New Zealand for carbon taxes.

### *11.4.2 Policy Analysis of the Effects of the Kyoto Protocol*

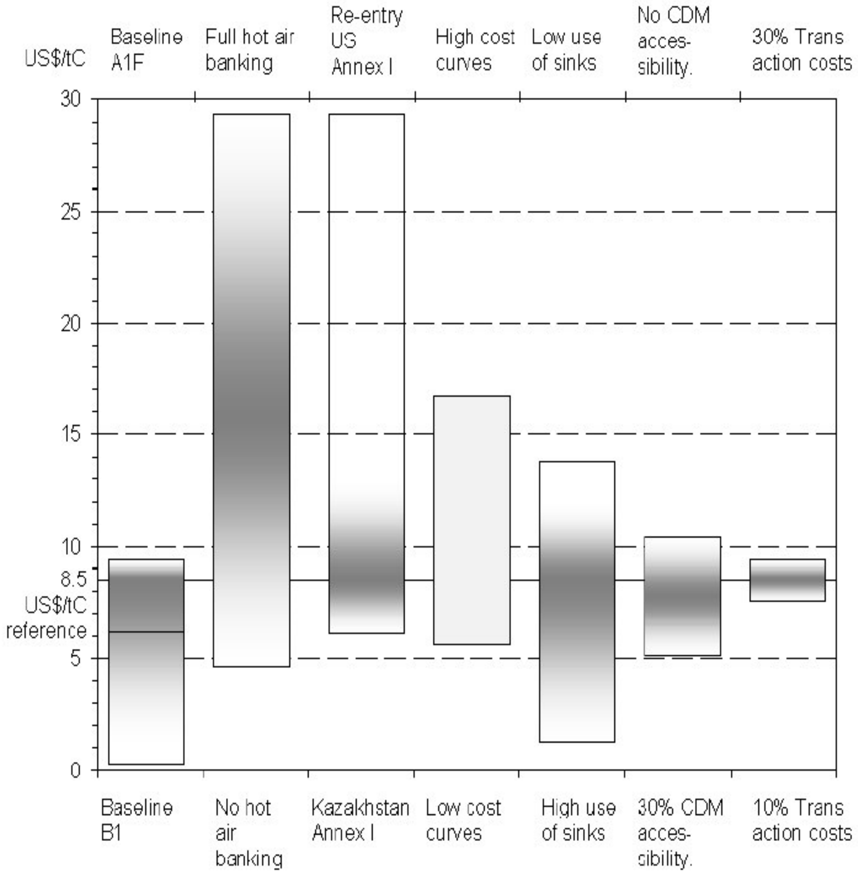
Most analyses reported in the TAR focused on national emission policies under the Kyoto Protocol in the form of an economy-wide tax or tradable permit system. This continues to be active area of policy modelling as the Kyoto Protocol has come into force. Global cost studies of the Kyoto Protocol since 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 withdrawal 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, 2003b; McKibbin and Wilcoxen, 2003; Klepper and Peterson, 2005). Figure 11.3 provides one estimate of the impact of different assumptions about the answers to these questions on the equilibrium permit price.

5 ***Figure 11.3:*** *Key sensitivities for the emission permit price from the FAIR model applied to the Kyoto Protocol under the Bonn-Marrakesh Accords. Source: den Elzen and Both (2002, p.43).*



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 while in the HIGH case, all hot air is banked; the reference case is one in which hot air banking is optimal for the Annex-I FSU (see Figure 5.7 in Section 5.6).
- ☐ *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 CDM sink credits capped to 0.5 per cent of base year emissions (instead of 1 per cent), 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 195 MtC of carbon credits from sinks-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 per cent 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 per cent.
- ☐ *Transaction costs:* the transaction costs associated with the use of the Kyoto Mechanisms is set at 20 per cent in the reference case, at 10 per cent in the LOW case and at 30 per cent in the HIGH case.



The U.S. withdrawal from the Kyoto Protocol, coupled with the increase in sink budgets in Bonn and Marrakech, implies that the aggregate target for Annex B countries as a whole will likely be met with virtually no effort. That is, 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 behavior by Russia and Ukraine, acting as a supply cartel and/or choosing to bank allowances until the next commitment period, leads to a positive emission price (Löschel and Zhang, 2002; Böhringer and Löschel, 2003b; Klepper and Peterson, 2005). Others point out the importance of CDM supply (den Elzen and de Moor, 2002)

### *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-detail that is difficult to achieve in the context of a global model. We briefly summarize the results of studies for various countries / blocks.

#### 11.4.3.1 Policy Studies for the United States

Following U.S. rejection of the Kyoto Protocol, there have been a number of policy proposals in the United States, 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). Costs and other consequences of those proposals are summarized in Table 11.11, as compiled by Morgenstern (2005) from studies by the U.S. Energy Information Administration (Energy Information Administration (EIA), 1998; Energy Information Administration (EIA), 2004; Energy Information Administration (EIA), 2005).

*Table 11.11: The EIA's Analysis of the Kyoto Protocol, McCain-Lieberman Proposal, and Bingman/NCEP Proposal: US in 2020.*
*Source: Morgenstern (2005)*

| | Bingaman | McCain-Lieberman | Kyoto (+9%) |
|---|---|---|---|
| GHG emissions (% domestic reduction) | 4.5 | 17.8 | 23.9 |
| GHG emissions (tons $CO_2$ reduced) | 404 | 1346 | 1690 |
| Allowance price ($2003 per ton $CO_2$) | 8 | 35 | 43 |
| Coal use (% change from forecast) | -5.7 | -37.4 | -72.1 |
| Coal use (% change from 2003) | 14.5 | -23.2 | -68.9 |
| Natural gas use (% change from forecast) | 0.6 | 4.6 | 10.3 |
| Electricity price (% change from forecast) | 3.4 | 19.4 | 44.6 |
| Potential GDP (% loss) | 0.02 | 0.13 | 0.36 |
| Real GDP (% loss) | 0.09 | 0.22 | 0.64 |

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 forecast, the model produces a remarkably consistent set of estimates with most physical quantities (including emission reductions) varying roughly linearly with allowance price, and potential GDP impacts in absolute amounts as the price squared. Real GDP impacts, which include business cycle effects, are less consistent and depend both policy timing as well as assumptions about revenue recycling, e.g. 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 (EIA1998).

As an independent, government statistical agency, EIA's modelling results tend to lie at the center of most policy debates in the U.S.. Researchers at MIT also provided estimates of impacts associated with the McCain-Lieberman proposal that had similar allowance prices but differed in other ways (Paltsev *et al.*, 2003). A discussion by EIA (EIA 2003) points specifically to more demand reduction and less fuel switching in the MIT analysis, consistent with observations that more top-down models, such as MIT's EPPA model, tend to have more elastic demand. Harder to explain is the roughly 3-4 times higher potential GDP costs in the EIA analyses, even as allowance prices and emission reductions are the same. One reason is that the EIA uses an econometric model to compute macroeconomic (e.g., GDP) costs, a model that, in turn, embeds assumptions about energy price impacts on GDP unrelated to marginal abatement costs. The MIT and other CGE models assume that, to a large extent, aggregate costs equal the accumulated marginal costs of abatement. These models tend to yield lower costs than the econometric models (Repetto and Austin, 1997).

A threshold question in the McCain-Lieberman discussion has been whether 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) using a CGE model shows that exclusion of these sectors has little impact on costs. However, excluding industry roughly doubles costs while implementing energy-efficiency 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.

In addition to the aforementioned studies focusing on recent policy proposals, additional work on costs in the U.S. has focused on distribution. Rose and Oladosu (2002) and Dinan (2004) both document regressive impacts of climate change policy, noting that grandfathering allowances in an emissions trading program is more regressive than auctioning allowances and recycling the revenue via a decline in income taxes or a lump-sum rebate. Bovenberg and Goulder (2001) consider a different distributional question: how much do energy industries require to offset losses in profit from a cap-and-trade program? Their answer, that grandfathering roughly 15% of the allowances, and auctioning the rest, fully offsets the industry-wide effects, has motivated additional interest in allowances.

A large number of recent climate policy proposals in the U.S. have been put forward by states. Analysis of a package of 8 sectoral efficiency measures in the context of a cap-and-trade scheme using a CGE model (Roland-Holst, 2006) reduces 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 (Hanneman *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, for example, demonstrates (see US NHTSA 2006).

### 11.4.3.2 Policy Studies for Canada

Jaccard *et al.* (2003b) provide estimates of costs of reaching the Kyoto targets in Canada as part of their larger 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 150 C\$/tCO$_2$e with an associated GDP loss of nearly 3%. 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 - predicting a roughly C\$50 allowance price. The authors then show how by making what they consider longer-run assumptions - lower capital and intangible costs as well as 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 been analysing the macroeconomic costs in Europe of committing to Kyoto or other targets, different trade regimes, and multiple greenhouse gases. Below we report results from some of the key studies.

An important development within the European Union has been additional detailed results by individual member states. Viguier *et al.* (2003) provide a comparison of four model estimates of the costs of meeting Kyoto targets without trading based on the 1998 burden sharing agreement, replicated in Table 11.12. 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 among 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 domestic 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, in between the estimates of POLES and PRIMES.

***Table 11.12:*** *A comparison of (a) model estimates of domestic carbon prices, (b) EPPE-EU model estimates of welfare, GNP and terms of trade for the EU ETS in 2010 to achieve the Kyoto target 2010*

(a) A comparison of model estimates of domestic carbon prices

| | EPPA US\$95/tC | GTEM US\$95/tC | POLES US\$95/tC | PRIMES US\$95/tC |
|---|---|---|---|---|
| Germany | 119 | 177 | 107 | 88 |
| France | 136 | - | 220 | 144 |
| UK | 91 | 113 | 133 | 123 |
| Italy | 147 | - | 352 | 173 |
| Rest of EU | 160 | - | - | 221 |
| Spain | 184 | - | - | 134 |
| Finland | 217 | 289 | - | 150 |
| Netherlands | 293 | - | - | 536 |
| Sweden | 310 | 358 | - | 219 |
| Denmark | 385 | 400 | - | 189 |
| EU | 159 | 155 | 188 | 135 |
| USA | 229 | - | 177 | - |
| Japan | 201 | - | 238 | - |

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

(b) A comparison of EPPA-EU estimates of wefare, GNP and terms of trade

| | Welfare | GDP | Terms of trade |
|---|---|---|---|
| Germany | 0.63 | 1.17 | 1.1 |
| France | 0.67 | 1.11 | 1.11 |
| UK | 0.96 | 1.14 | 0.77 |
| Italy | 1.01 | 1.47 | 1.54 |
| Rest of EU | 1.23 | 2.12 | 1.07 |
| Spain | 2.83 | 4.76 | 2.06 |
| Finland | 1.90 | 2.73 | 1.67 |
| Sweden | 3.47 | 5.11 | 1.18 |
| Denmark | 3.97 | 5.72 | 0.74 |
| Netherlands | 4.92 | 7.19 | 0.55 |
| USA | 0.49 | 1.01 | 2.39 |
| Japan | 0.22 | 0.49 | 2.7 |

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, with France, the United Kingdom, and Germany facing lower costs and Scandinavian countries generally facing 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 still other studies estimating the equilibrium price in the European market for tradable permits and the savings versus a no-trade case. An early study by IPTS (2000) calculates the clearing price in the EU market in 2010 to be 49 €/t$CO_2$ using the POLES model, with a 25% cost reduction arising from emissions trading among countries and Germany and the UK arising as net sellers. A more recent study by Criqui and Kitous (2003) also using the POLES finds even larger gains and lower prices: the equilibrium allowance price is 26 €/t$CO_2$ and trading among countries reduces the 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 €/t$CO_2$ to less than 5 €/t$CO_2$, and the annual compliance costs are reduced by another 60%. Böhringer and Löschel (2002) 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, with costs of 0.1 to 0.2% for the EU15+EFTA and benefits of 0.2 to 0.9% for the Central European States. Using the PRIMES model, Svendsen and Vesterdal (2003) find reductions in costs of 13% from trading within the electricity and steam sector in the EU, 32% EU economy-wide trading, and 40% from Annex B trading.

Eyckmans *et al.* (2000) investigate the EU Burden Sharing Agreement on the distribution of the Kyoto emissions reduction target over the EU member states. Even if only cost efficiency is taken into account, they argue that the burden sharing agreement does not go far enough towards equalising 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. European Commission (1999) finds that at a cost below 50 ECU/ton $CO_2$ eq, 42 per cent 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%,.

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

Summarizing, the costs of committing to the Kyoto Protocol may not be very high in Europe with flexible trading. U.S. rejection of the Kyoto Protocol, increases the cost of commitment in Europe if there were no emissions trade or other flexible mechanisms, due to terms of trade effects, but otherwise lowers costs. The permit price and costs depend on restrictions to trade and the possible exercise of market power in the emission permit market. The costs will also vary across countries, with France, the United Kingdom, and Germany facing lower costs and Scandinavian countries and the Netherlands generally facing higher costs. Multiple greenhouse gas abatement will reduce costs compared to a situation with only $CO_2$ abatement, a point emphasized in 11.4.4 below.

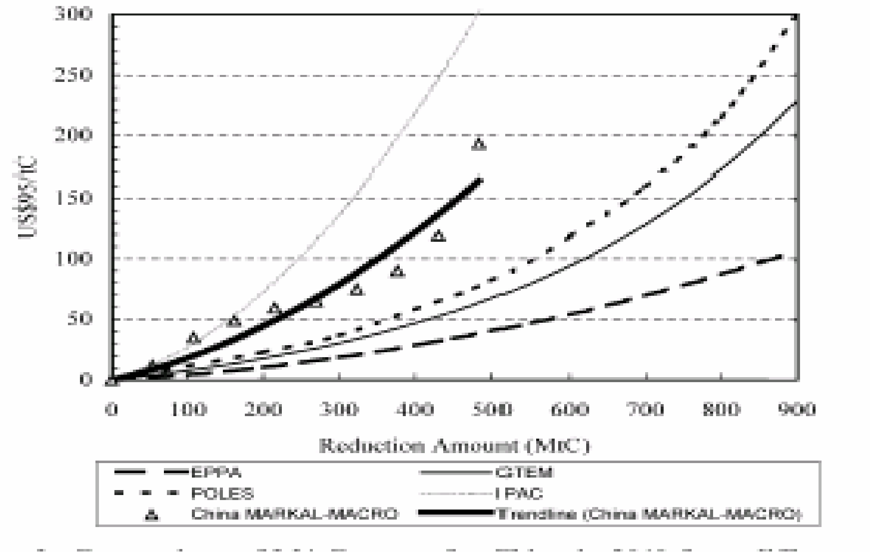
#### 11.4.3.4 Policy Studies for Japan

Masui *et al.* (2005) estimate that a $410 carbon tax would be necessary to achieve the Kyoto target in Japan. With revenues used to subsidize new technologies, they estimate a tax of only $31/tC is necessary. In contrast, Hunt and Ninomiya (2005) look at emission trends and argue that as long as growth is less than 1%pa, and the carbon intensity of energy does not rise, Japan should be able to achieve their target, e.g., through the Kyoto Target Achievement Plan. If growth is closer to 2%pa, it will be nearly impossible.

#### 11.4.3.5 Policy Studies for China

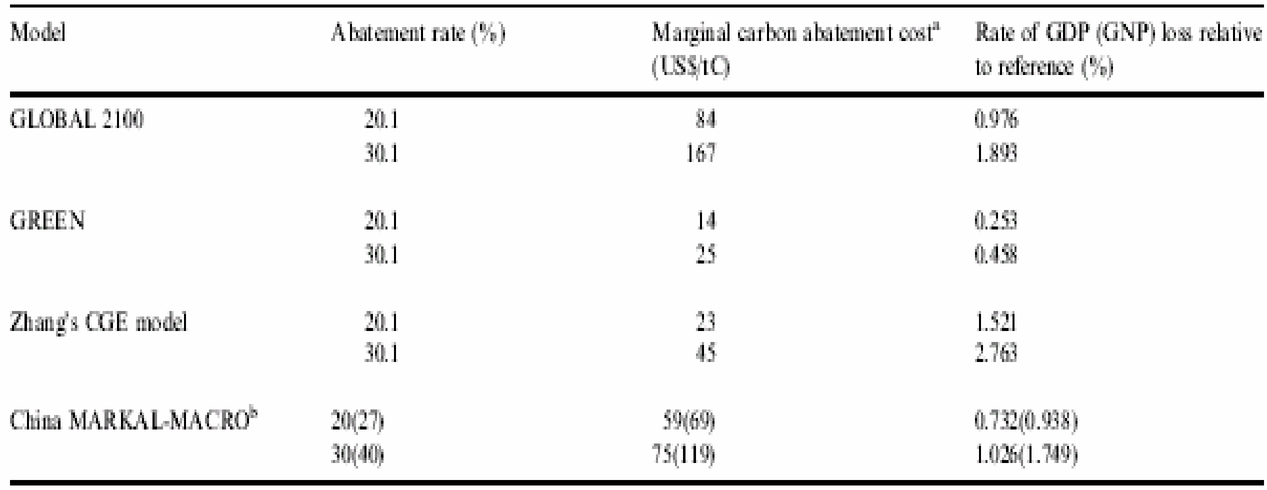
Chen (2005) presents a comparison over different models of estimated marginal abatement cost schedules and GDP costs associated with various reduction efforts in China (see Figure 11.4 below). Table 11.13 shows estimates of GDP costs for 2010 of between 0.2 and 1.5% associated with a 20% abatement rate, and between 0.5 and 2.8% associated with a 30% abatement rate. Garbaccio *et al.* (1999) consider smaller 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.

***Figure 11.4:*** *A comparison of Marginal Abatement Curves for China in 2010 from different models. Source: Chen, (2005, p.891).*



*11.4.4 Post-Kyoto Studies*

***Table 11.13:*** *A comparison of GDP loss rates for China across models in 2010*
*Notes: 1) Marginal carbon abatement costs were originally measured at 1990 prices in GLOBAL 2100, at 1985 prices in GREEN, and at 1987 prices in Zhang's CGE model, but were converted to 1995 prices in order to be compared with that from China MARKAL-MACRO.*
*2) The figures in parentheses indicate the percentage of reductions required, the associated marginal abatement costs and the GDP loss rates in order to achieve the same amount of carbon reductions as those in Zhang's model.*
Source: Chen, (2005, p.894)



| Model | Abatement rate (%) | Marginal carbon abatement cost[a] (US$/tC) | Rate of GDP (GNP) loss relative to reference (%) |
|---|---|---|---|
| GLOBAL 2100 | 20.1 | 84 | 0.976 |
| | 30.1 | 167 | 1.893 |
| GREEN | 20.1 | 14 | 0.253 |
| | 30.1 | 25 | 0.458 |
| Zhang's CGE model | 20.1 | 23 | 1.521 |
| | 30.1 | 45 | 2.763 |
| China MARKAL-MACRO[b] | 20(27) | 59(69) | 0.732(0.938) |
| | 30(40) | 75(119) | 1.026(1.749) |

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 participating in emission trading, the high-growth benchmark case shows an allowance price of €129/tCO2, with a

2.2% reduction below baseline for Annex I GDP. With global-trading, the allowance price is €17/t$CO_2$ and there is a much lower loss of 0.6% in GDP.

A number of other studies consider post-Kyoto impacts out to 2025 or 2050 based on approaches to stabilize concentrations, typically at 550 ppm $CO_2$ eq (in the B category of Table 3.5) (longer-term strategies are discussed in Chapter 3; discussions of policy mechanisms are covered in Chapter 13). Den Elzen *et al.* (2005), for example, show that different assumptions about business as usual emission levels and abatement cost curves lead to a range of marginal costs of between $50 and $200 per ton of $CO_2$, and of total costs of between 0.4 and 1.4% of world GDP, in 2050.

#### 11.4.4.1 Allocation Scenarios

The bulk of their paper, however, is about the distribution of costs under different global allocation scenarios, and particularly ones that might attract developing country participation. They consider approaches based on convergence to equal per capita emission rights, a multi-stage approach where countries graduate to more significant commitments as their income rises, and a “Brazilian” approach based on historic contributions to atmospheric GHGs. Generally, allocations do not have an effect on total costs; which in their central case remain at 0.4% of total GDP in 2025, 1% in 2050, for all 550 ppm allocation cases. All of these allocations also suggest positive trade flows to Africa and South Asia, but net costs everywhere else. Among other regions, they note that regions with medium to high per capita emissions, but medium to low income (including the FSU, the Middle East and Turkey), fare the worst with 3-4% GDP losses by 2050 and will tend to prefer allocation schemes with income thresholds. Persson *et al.* (2006) similarly find that Africa experiences large trade flows with various per capita convergence allocations, especially one that begins quickly, but they are more equivocal about South Asia. China, they find, will almost certainly experience net costs under any convergence criteria. Criqui *et al.* (2003) also review such allocation approaches as also covering ability to pay based on GDP and other equity principles such as sovereignty (future emission rights based on current levels) and polluter pays (future reduction obligations based on current emission levels). A key observation in their analysis is that for the 550 ppm $CO_2$ eq target, welfare impacts are driven by sales and purchases of emission allowances (except for the Middle East region), while terms of trade effects are less important at lower concentration targets. Overall, they conclude that the multi-stage approach offers better outcomes for developing countries precisely because it provides them with a higher allowance allocation.

Buchner and Carraro (2003) take a slightly different approach considering particular coalitions for specific countries. Focusing on the U.S., China, and Russia (who at the time had not ratified the protocol), they find that different coalitions favor different countries. Continuing to move from prescriptive allocation approaches toward descriptive analyses of what might happen, Böhringer and Löschel (2003a) survey experts about the likely shape of emission commitments in 2020 and then report the cost consequences. Specifically, they look at the likely level of emission reductions, the participation of the United States, the participation of developing countries, and the likely allocation rule. It is worth noting that they find that 61% of the surveyed experts expect global emission reductions of 10% or less from BAU by 2020. Only 12% of surveyed experts expected an egalitarian or per capita approach. The authors then draw a number of conclusions from looking at various scenarios suggested by the survey results. Without commitments, developing countries as a whole usually find zero effect on their GDP, with indirect terms of trade effects and direct effects from selling emission reduction balancing out. With commitments based on 2010 emission levels and no compensation, they bear the entire burden of global emission reductions. Overall costs are virtually unchanged, with a 0.05% consumption loss, across scenarios except when the United States is completely out of the program.

Summarizing, there have been a variety of post-2012 Kyoto studies completed since the TAR. Focusing mostly on 550ppm $CO_2$ eq stabilization targets (Category B, Table 3.5) over the next 25-50 years (perhaps a 30% reduction in global $CO_2$ in BAU by 2025), they find total costs on the order of 1% of global GDP -- with the critical assumptions of global emissions trading, but no induced technological change, no benefit from multi-gas stabilization and no co-benefits. As noted in sections 11.5 and 11.6 (induced technological change), 3.3.5.4 and 11.6 (multi-gas approaches), and 11.8.2 (co-benefits), these considerations will tend to lower costs, perhaps substantially. More relaxed emission targets also imply lower costs, and may be more likely, based on expert surveys.

### *11.4.5 Differences Across Models*

Research has continued to focus on differences in various cost estimates across models (Weyant, 2000; Weyant, 2001; Lasky, 2003; Weyant, 2003; Fischer and Morgenstern, 2005; Barker *et al.*, 2006). Weyant (2001) argues that the five major determinants of costs are projections for base case GHG emissions, the climate policy (e.g., flexibility), substitution possibilities among producers and consumers, the rate and process of technological change, and the characterization of mitigation benefits. In terms of base case, he notes the importance of assumptions about population and economic activity, resource availability and prices, and technology availability and costs. The key policy feature is flexibility - whether trading across firms, 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 as technologies are increasingly used. Finally, mitigation benefits may be included in varying degrees among models.

The factors accounting for differences between the cost estimates can be divided into three groups: features inherent in the economies being studied (e.g. high substitution possibilities at low cost), assumptions about policy (e.g. use of international trading in emission permits, or whether auction revenues are recycled), 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, the differences in modellers' approaches and assumptions remain in the treatment of substitution and technology. The various factors can be disentangled by means of meta-analysis of published finding. This technique was first used by Repetto and Austin (1997) in a mitigation-cost analysis of GDP costs for the US economy. Fischer and Morgenstern (2005) conduct a similar meta-analysis but on the carbon prices (taken to be the marginal abatement costs) of achieving Kyoto targets in the EMF16 studies reported 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, e.g. that 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 greater disaggregation of product and regional markets. This suggests that any particular set of results on costs may well be the outcome of the particular assumptions and characterisation of the problem chosen by the model builder, which may not be replicated by others choosing different assumptions.

Both Fischer and Morgenstern (2005) and Lasky (2003) identify treatment of trade and the disaggregation of the energy sector as important factors leading to differences. Lasky also identifies the sizes of the energy-demand elasticity and sensitivity 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 standardised energy-price sensitivity, and including non-$CO_2$ gases and sinks, but excluding recycling benefits and any ancillary benefits from improved air quality. The change falls to 0.2% of GDP with global trading of permits. Barker and Ekins (2004) review the large number of modelling studies on the costs of Kyoto for the US economy available at the time 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 (EIA1998). The review confirms Lasky's range of costs but offsets these with benefits from recycling the auctioned-permit revenues and the environmental benefits of lower air pollution. These co-benefits of mitigation are discussed in section 11.8 below.

## 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 treatment on emission permit prices, carbon tax rates, GDP and/or economic welfare, and policy modelling (Chapter 2, section 9 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 11.14 lists the implications for modelling of exogenous and induced technological change and demonstrates the challenges for research. The table shows that, at least in their simplified forms, the two types of innovation processes potentially carry very different policy implications in a number of different dimensions.

*Table 11.14: 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 |
| | | |
| Optimisation 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 stabilisation below c.550ppm $CO_2$ likely to be very costly without explicit assumption of change in autonomous technology trends. | Stringent atmospheric stabilisation may or may not be very costly based 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 suggests 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 little 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, positive spillovers also exist (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). Both analyses cover large numbers of modelling studies undertaken before 2000 and both 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, though syntheses of this work tends to reveal wide differences in theoretical approach, and results that are strongly dependent on a wide range of assumptions adopted, which are far from agreed (deCanio, 2003).

The approaches to modelling technological change (see section 2.9.2.1), include (1) explicit investment in research and development (R&D) that increases the stock of knowledge, (2) the (typically) costless accumulation of applying that knowledge through “learning-by-doing” (LBD); and (3) simple sensitivity analyses to cost assumptions (the latter reflecting a continued exogenous approach). These efforts have yielded an edited book (Grubler *et al.*, 2002) and four special issues of journals addressing the topic (*Resource and Energy Economics*, 2003, vol. 25; *Energy Economics*, 2004, vol. 26; *Ecological Economics*, 2005, vol.54; and *Energy Journa*l, 2006). There have been many reviews, including those in these issues; see (Clarke and Weyant, 2002; Grubb *et al.*, 2002b; Löschel, 2002; Jaffe *et al.*, 2003; Goulder, 2004; Weyant, 2004; Smulders, 2005; Vollebergh and Kemfert, 2005; Edenhofer *et al.*, 2006; Köhler *et al.*, 2006; Popp, 2006; Wing and Popp, 2006). One feature that emerges from the studies is the great variety in the treatment of technological change and its relationship with 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, particularly in the near-term costs to 2050. Some studies of endogenous technological change take a cost-benefit approach (eg. Nordhaus, 2002) and, given a relatively insensitive model of marginal benefits, typically find similar costs but differences in emission levels. That is, rather than revealing the effect of ETC on the costs of mitigation, they reveal the effect of ETC on optimal emission levels. This section 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.

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 to 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 11.15 shows the policies that have been modelled to induce technological change, and how they have been introduced into the models. The policies are in 2 groups: effects through R&D expenditure, and those through learning by doing. Unfortunately, our empirical understanding of these phenomena over long periods of time are no better - perhaps worse - than our ability to forecast exogenous rates of change. As Popp (2006) notes, none of the ETC models he reviews make use of empirical estimates of technological change to calibrate the models - because until recently, few empirical studies of innovation and environmental policy existed. Thus, while we are confident that mitigation costs will be lower than predicted by models assuming historically-based, exogenous rates of technological change, there remains a range of views as to how much lower.

*Table 11.15:* ***Technology policies and modelling approaches***

| Policies | Modelling approach | Key points for measuring costs |
|---|---|---|
| R&D in low-GHG products and processes from:<br>Corporate tax incentives for R&D (supply-push R&D)<br>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.<br>R&D policies can be modelling as explicit increases in R&D supply or subsidies to the R&D price. | the assumed rate of return to R&D, typically based on an assumption that substantial spillovers exist and that the rate of return to R&D is several times higher than conventional investment. Also important is the assumed cost of R&D inputs, which may be high if they are drawn from other R&D (crowding out) |
| Learning-by-Doing:<br>Purchase requirements or subsidies for new, low-GHG products<br>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 lower costs and long-run potential for costs to fall. |

### *11.5.2 Effects of Modelling Sectoral Technologies on Estimated Mitigation Costs*

The Energy Modelling Forum conducted a comparative study (EMF19) with the purpose of understanding 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, endogenous or exogenous, might affect estimates of aggregate costs for a 550 ppm $CO_2$ concentration target. The modellers emphasise the detailed representations for one or more technologies within integrated frameworks. Weyant (2004) summarizes the results, which show apparently small GDP costs (Fig. 2 p. 509) 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 11.5 shows that the carbon tax rates are very low before 2050, with all models indicating values below about $50US/tC to 2030 and 6 of the 9 below $100US/tC by 2050; for comparison the EU ETS price of carbon reached nearly $130US/tC (€30/t$CO_2$) in August 2005 and again in April 2006.

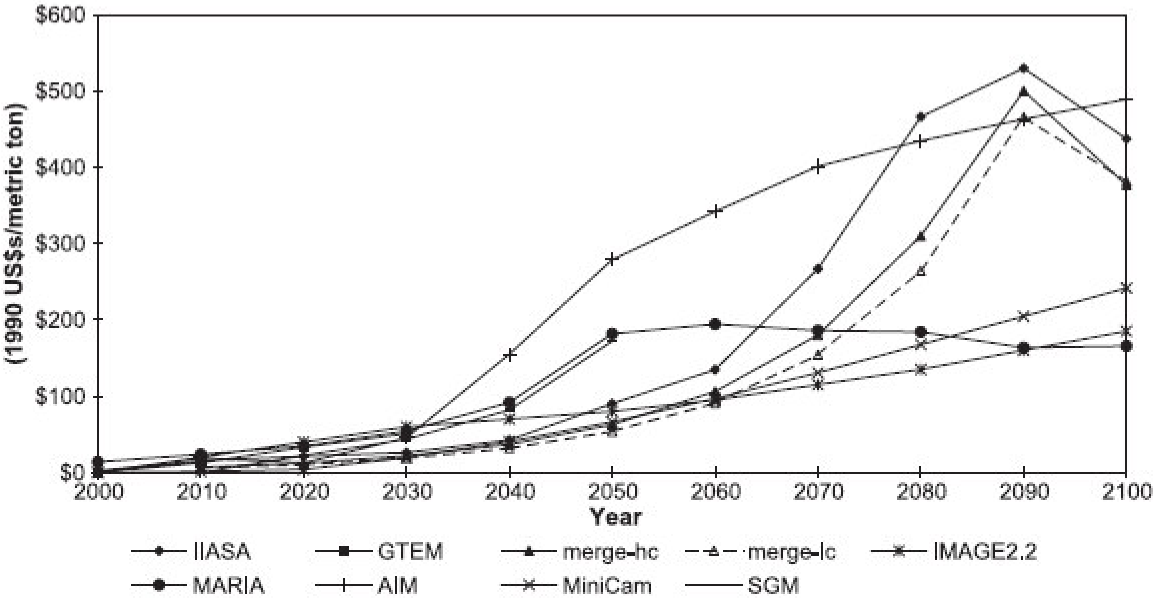


*Figure 11.5: Carbon tax projections for the 550mmpv* $CO_2$*-only stabilization scenario. Source: Weyant (2004).*

Perhaps more revealing in the EMF19 study is the chosen focus by various modelling teams in their respective papers. Six teams focused on carbon capture and sequestration (Edmonds *et al.*, 2004b; McFarland *et al.*, 2004; Riahi *et al.*, 2004; Sands, 2004; Smekens-Ramirez Morales, 2004) Kurosawa 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). 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 piece determining long-run 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, while end-use efficiency may offer important opportunities in the nearer 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 research and development (R&D) activities that contribute to a knowledge stock and reduce costs, and the costless accumulation of knowledge through learning-by-doing (LBD). Sijm (2004) and Edenhofer *et al.* (2006) 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.

***Table 11.16:*** *Overview of top-down modelling approaches on the impact of induced technological change and spillovers on climate policy performance. Source: Sijm (2004)*

| Study | Model | ITCchannel | Spillovers | Policy instrument | Focus of analysis | Major results (impact of ITC) | Comments |
|---|---|---|---|---|---|---|---|
| Goulder and Mathai (2000) | Partial cost-function model with central planner | R&D<br>LBD | No | Carbon tax | Optimal carbon tax profile<br>Optimal abatement profile | Lower time profile of optimal carbon taxes. Impact on optimal abatement varies depending on ITC channel<br>Impact on overall costs and cumulative abatement varies, but may be quite large | Deterministic<br>One instrument<br>High aggregation<br>Weak database |
| Goulder and Schneider (1999) | General equilibrium multi-sectoral model | R&D | Yes(sectoral) | Carbon tax | Abatement costs and benefits | Gross costs increase due to R&D crowding-out effect<br>Net benefits decrease | Lack of empirical calibration<br>Focus on U.S.<br>Full ‘crowding out’ effect |
| Nordhaus (2002) | R&DICE (global IAM, Top-down, neoclassical) | R&D | Implicit(social > private rate of return) | Carbon tax | Factor substitution versus ITC<br>Carbon intensity<br>Optimal carbon tax | ITC impact is lower than substitution impact and quite modest in early decades | Deterministic<br>Full ‘crowding out’ of R&D<br>High aggregation (global, one sector) |
| Buonanno *et al.* (various)a | FEEM-RICE (6-8 regions, single sector)<br>Top-down | R&D (and occasionally LBD) | Yes | Rate of carboncontrol<br>Emissions Trading (plus ceilings) | Compliance costs of Kyoto protocol<br>Impact of ET (+ restrictions) | Direct abatement costs are lower, but total costs are higher. ET ceilings have adverse effects on equity and efficiency | Includes international spillovers<br>No crowding-out effect |
| Gerlagh and Van der Zwaan (various)b | DEMETER One-sector Two technologies | LBD | No | Carbon tax | Optimal tax profile<br>Optimal abatement profile. Abatement costs | Costs are significantly lower<br>Transition to carbon-free energy<br>Lower tax profile. Early abatement | Results are sensitive to elasticity of substitution between technologies as well as to the learning rate on non-carbon energy |
| Study | Model | ITCchannel | Spillovers | Policy instrument | Focus of analysis | Major results (impact of ITC) | Comments |
| Popp (2004c) | ENTICE (based on Nordhaus’ DICE) | R&D | Implicit | Carbon tax | Welfare costs<br>Sensitivity analysis of R&D parameters | Impact on cost is significant<br>Impact on emissions and global temperature is small | Partial crowding out effect |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Rosendahl (2002) | Builds on Goulder and Mathai (2000) | LBD | Yes(industrial and regional) | Carbon tax<br>Emissions trading | Optimal carbon tax (or permit price) over time in two regions. Optimal ET + restrictions | ET restrictions are cost-effective<br>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 |
| Kverndokk *et al.*. (2001 and 2003) | Applied Computable General Equilibrium (CGE) model for small open economy | LBD | Yes (sectoral) | Carbon tax<br>Technology Subsidy | Optimal timing and mixture of policy instruments<br>Welfare effects of technology subsidies | Innovation subsidy is more important in the short term than a carbon tax<br>Innovation subsidy may lead to 'picking a winner' and 'lock in' | |
| Sue Wing (2003) | Multi-sector CGE (U.S.) | R&D | No | Carbon tax | Macroeconomic costs<br>Allocation of R&D resources | ITC impact is positive and large in reducing social costs | Outcome is due to the substitution effect of homogenous knowledge factor |
| Bollen (2004) | WorldScan (12 regions, 12 sectors) | R&D | Yes (sectoral, regional) | Carbon tax (+ recycling) | Income and production losses | ITC magnifies income losses | Sectoral R&D intensities stay constant overtime |

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a) See, for instance, Buonanno *et al.* (2000 and 2003); Galeotti *et al.* (2002 and 2003); Buchner *et al.* (2003); and Carraro (2003).

b) See, for instance, Gerlagh and Van der Zwaan (2003); Gerlagh *et al*. (2003); Van der Zwaan *et al*. (2002) and Van der Zwaan and Gerlagh (2003).

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, described in Table 11.16, he finds considerable variation in the effect of including ETC. While some models find a large reduction in mitigation costs (e.g. Sue Wing 2000), some find small impacts (eg. Nordhaus, 2002). These differences can be attributed to:

- the extent of substitution allowed in the models of low-carbon fuels for high-carbon fuels - when it 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 treatment of spillovers - in addition to justifying higher rates of return to R&D, spillovers imply that the market outcome is sub-optimal with too little investment, providing an avenue for welfare improvements;
- the degree of differentiation among R&D activities, the assumed rates of return to those activities, and capacity for 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 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 long-run substitution between low-carbon and high-carbon energy (Goulder and Mathai, 2000; Nordhaus, 2002; Popp, 2006), show lower effects of R&D than those that do, e.g. by introducing a carbon-free backstop technology (Gerlagh and Lise, 2005; Popp, 2006). 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.*, 2006, p. 104).

Providing evidence of 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; Popp, 2004) differ considerably on the extent of crowding out. That is, 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 - carbon-saving R&D has a social rate of return that is four times the private rate of return, but because it is assume to be drawn from 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.

What is the correct degree of crowding out? Popp (2006), in turn, suggests from the empirical evidence that one-half of the energy R&D spending that took place in the 1970s and 1980s came at the expense of other R&D. Something between full and partial crowding out appears more recently in Gerlagh and Lise (2005) who find more than twice as much mitigation at a given price, but do not consider the cost savings for a given level of mitigation.

Goulder and Matthai (2000) provide an example of the importance of parameters describing returns to R&D and capacity for innovation to reduce costs. They compare both R&D as new knowledge and learning-by-doing LBD, finding a 29% in the tax rate with R&D by 2050 and 39% with LBD. As they note, however, this reflects their calibration to a 30% cost saving based on Manne and Richels (1992). Model results are simply reflecting the choice of calibrated parameter values.

In contrast to the results for top-down models, Sijm (2004) finds considerably more consistency among bottom-up models, where the effects of learning by doing typically lower costs by 20% to 40% over the next half-century, and by 60% to 80% over the next century. Importantly, these numbers are relative to a static technology alternative. As an alternative, 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 variation in estimated effects of learning on costs in bottom-up models are driven primarily by variation in the assumed rate of learning; that is, how much costs decline 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. Among four leading models, these learning rates vary by as much as a factor of two for a given technology, as shown in Table 11.17.

***Table 11.17:*** *Learning rates of electricity generating technologies in bottom-up energy system models.*

(a) one-factor learning curves

| [%] | ERIS | MARKAL | MERGE-ETL | MESSAGE |
|---|---|---|---|---|
| Advanced coal | 5 | 6 | 6 | 7 |
| Natural gas combined cycle | 10 | 11 | 11 | 15 |
| New nuclear | 5 | 4 | 4 | 7 |
| Fuel cell | 18 | 13 | 19 | - |
| Wind power | 8 | 11 | 12 | 15 |
| Solar PV | 18 | 19 | 19 | 28 |

(a) two-factor learning curves

|  | ERIS |  | MERGE-ETL |  |
|---|---|---|---|---|
| [%] | LDR | LSR | LDR | LSR |
| Advanced coal | 11 | 5 | 6 | 4 |
| Natural gas combined cycle | 24 | 2 | 11 | 1 |
| New nuclear | 4 | 2 | 4 | 2 |
| Fuel cell | 19 | 11 | 19 | 11 |
| Wind power | 16 | 7 | 12 | 6 |
| Solar PV | 25 | 10 | 19 | 10 |

Notes: 1) In MERGE-ETL, endogenous technological progress is applied to eight energy technologies: six power plants (integrated coal gasification with combined cycle, gas, turbine with combined cycle, gas fuel cell, new nuclear de-signs, wind turbine and solar photovoltaic) and two plants producing hydrogen (from biomass and solar photo-voltaic). Furthermore, compared to the original MERGE model, Bahn and Kypreos (2002 and 2003) have introduced two new power plants (using coal and gas) with $CO_2$ capture and disposal into depleted oil and gas reservoirs.
2) For a review of the literature on learning curves, including 42 learning rates of energy technologies, see McDonald and Schrattenholzer, 2002.
3) For a discussion and explanation for similar (and even wider) variations in estimated learning rates for wind power, see Söderholm and Sundqvist (2003) and Neij et al. (2003a and 2003b).

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

4) Learning rates are defined as the percent reduction in unit cost associated with a doubling of output.

The modelling of LBD is however beset with problems. Model solutions become more complex. Avoidance of multiple solutions typically requires that the penetration of new technologies is constrained, making one element of the cost reduction effectively exogenous. Since many low-carbon technologies are early in the learning process compared with mature energy technologies, it becomes inevitable that they increase and eventually take over at the social unit costs of carbon become higher. Finally, the treatment often assumes that the diffusion and accompanying R&D are costless, although the investments required for the technologies with high learning rates are comparable with those that are replaced.

In addition, the measurement of learning rates faces econometric problems. It is difficult to separate the effects of time trends 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.

A second survey of ETC effects on aggregate mitigation costs comes from the Innovation Modelling Comparison Project (Edenhofer *et al.*, 2006). Rather than reviewing previous results, the IMCP engaged modelling teams to report results for specific concentration scenarios and, in particular, with and without their ETC elements turned on. 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 so that technology is not “static” in the sense of being fixed in the initial time period. This baseline technology path can then be either fixed or allowed to change in response to the climate policy.

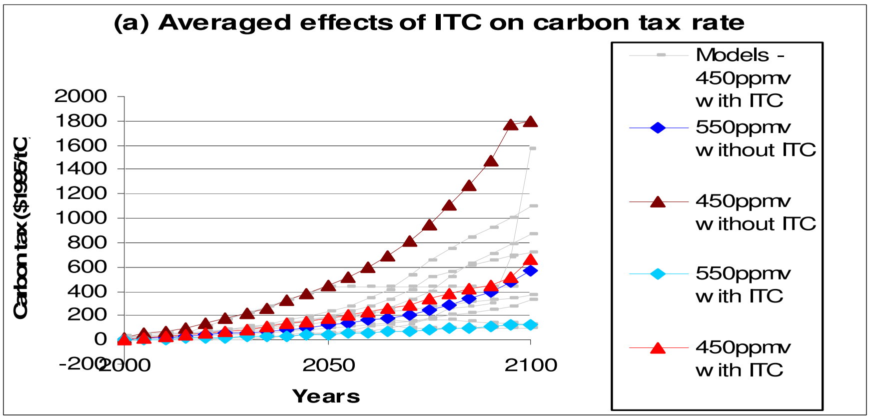
***Table 11.18:*** *Treatment of endogenous technological change (ETC) in some global integrated assessment model*
Source: (Edenhofer *et al.*, 2006)
Note: See source for details of models.

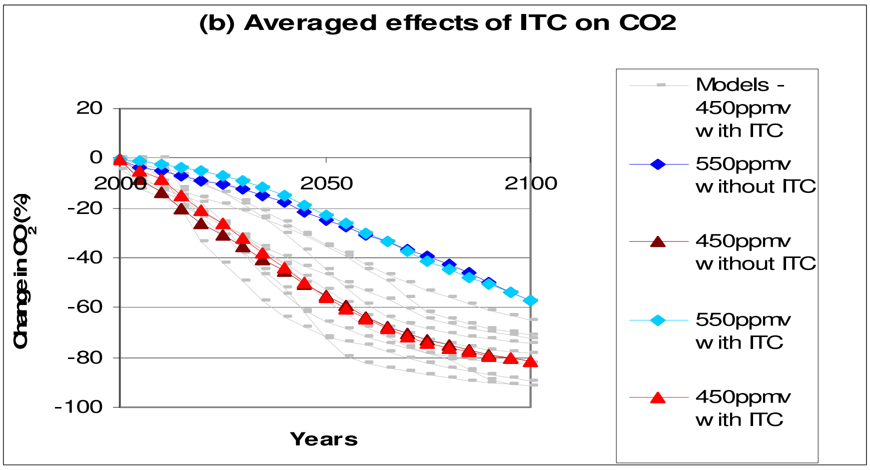
| Model | Model type | ETC related to energy intensity | ETC related to carbon intensity | Other ETC | Exogenous technological change |
|---|---|---|---|---|---|
| IMACLIM-R | Dynamic recursive growth model | Cumulative investments drive energy efficiency<br>Fuel prices drive energy efficiency in transportation and residential sector | Learning curves for energy technologies (electricity generation) | Endogenous labor productivity, capital deepening | |
| DEMETER-1CCS | GE market model | Factor substitution in CES production | Carbon-free energy from renewables and CCS<br>Learning-by-Doing for both | Learning-by-Doing for fossil fuels | Overall productivity |
| AIM/Dynamic-Global | Growth mode | Factor substitution in CES production<br>Investments in energy saving capital raises energy efficiency for coal, oil, gas, and electricity (in addition to AEEI) | Carbon-free energy from backstop technology (nuclear/renewables) | | AEEI for energy from coal, oil, gas, and for electricity |
| ENTICE-BR | endogenous growth IAM | Factor substitution in Cobb-Douglas production<br>R&D investments in energy efficiency knowledge stock | Carbon-free energy from generic backstop technology<br>R&D investments lower price of energy from backstop technology | | Total factor productivity<br>Decarbonization accounting for e.g. changing fuel mix |
| **FEEM-RICE** | Endogenous growth IAM | Factor substitution in Cobb-Douglas production<br>Energy technological change index (ETCI) increases elasticity of substitution<br>Learning-by-Doing in abatement raises ETCI<br>R&D investments raise ETCI | ETCI explicitly decreases carbon intensity<br>see ETCI in the energy intensity column | | Total factor productivity<br>Decarbonization accounting for e.g. changing fuel mix |
| **MIND** | Hybrid | R&D investments improve energy efficiency<br>Factor substitution in CES production | Carbon-free energy from backstop technologies (renewables and CCS)<br>Learning-by-Doing for renewable energy | R&D investments in labor productivity<br>Learning-by-Doing in resource extraction | Technological progress in resource extraction |

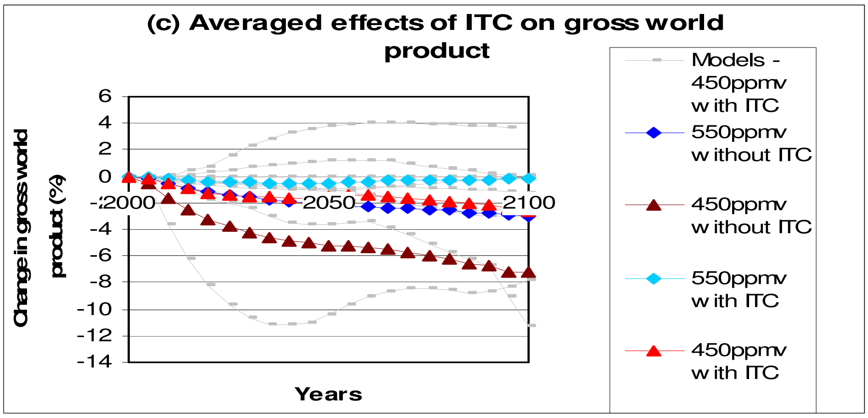
| Model | Model type | ETC related to energy intensity | ETC related to carbon intensity | Other ETC | Exogenous technological change |
|---|---|---|---|---|---|
| DNE21+ | ESM | Energy savings in end-use sectors modelled using the long-term price elasticity. | Carbon-free energy from backstop technologies (renewables, CCS, and nuclear)<br>Learning curves for energy technologies (wind, photovoltaic and fuel cell vehicle) | | Technological progress energy technologies (other than wind, photovoltaics, fuel cell vehicle) |
| **GET-LFL** | ESM | Learning-by-Doing in energy conversion | Carbon-free energy from backstop technologies (renewables and CCS)<br>Learning curves for investmenst costs<br>Spillovers in technology clusters | | |
| MESSAGE/ MACRO | ESM | Factor substitution in CES production in MACRO | Carbon-free energy from backstop technologies (renewables, carbon scrubbing and sequestration)<br>Learning curves for energy technologies (electricity generation, renewable hydrogen production) | | Declining costs in extraction, production<br>Demand |
| E3MG | Econometric | 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<br>Investments beyond baseline levels trigger a Keynesian multiplier effect | |
| IMAGE-TIMER | Simulation IAM | price elastic energy demand via substitution possibilities for energy by energy savings capital | Carbon-free energy from backstop technology (nuclear/renewables, CCS)<br>Learning-by-Doing for energy technologies (oil, gas, coal, nuclear, solar/wind, biomass) | Capital accumulation and depreciation | Efficiency of power plants, partly energy efficiency, transport and refining losses of fossil fuels and electricity |

Table 11.18 summarizes the treatment of technological change in the IMCP models; ideally, the wide range of approaches provides additional confidence in the results when common patterns emerge. Like Sijm (2004), Edenhofer *et al.* find that while ETC reduces mitigation costs, there continues to be a wide range of quantitative results - some near zero and others generating substantial reductions in costs. Figure 11.6 shows the effects of introducing ETC into the models averaged over all 9 sets of results for (a) carbon tax or $CO_2$ permit rates, (b) the changes in $CO_2$ and (c) changes in gross world product ($GW_p$). These solutions are with and without ETC for the 550 and 450ppmv $CO_2$ stabilization scenarios 2000-2100. The reductions in carbon prices and $GW_p$ are substantial for both scenarios. The effects on $CO_2$ show that including ETC in the models leads to earlier reductions in emissions, because LBD means that early action will have a greater effect on reducing overall costs in the optimizing models.

***Figure 11.6****: Averaged effects of including ETC on carbon tax rates, $CO_2$ emissions and gross world product: 9 global models 2000-2100 for the 450ppmv and 550ppmv $CO_2$ only stabilisation 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 $(1995)/tC, (b) changes in $CO_2$ (% difference from base) and (c) changes in gross world product (% differences from base). The results are shown with and without endogenous technological change. The gray background lines show the range from the models for 450ppmv with ITC.
See source for details of models.
Source: (Edenhofer *et al.*, 2006)

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 inefficient of resources in the baseline (distinct from the 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 modeled: recursive savings decisions, versus 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 would imply more crowding out.
- the modelling of substitution towards a backstop technology (e.g., a carbon-free energy source available at constant, albeit initially high, marginal cost): this can substantially affect the results, e.g. if investment in the technology is endogenous and exhibits learning by doing, then costs can fall dramatically. Popp goes further, and shows that the addition of a backstop technology by itself can have a larger effect than the addition of ETC.

In addition to examining the effect of ETC on mitigation costs, Edenhofer *et al.* 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. This suggests that, in designing an emissions trading scheme, it may be necessary have an aggressive, high price policy in the earlier years in order to generate innovation that provides benefits in later years.

### *11.5.4 Modelling Policies that Induce Technological Change*

Most of the studies noted so far only consider how endogenous technological change affects the cost associated with market-based approaches to limiting emissions. However, when spillovers are introduced into the model of ETC, e.g., where the social rate of return exceeds the private rate of return to R&D, this introduces a second market failure (in addition to the environmental externality associated with emission). Now, at least two instruments should be included for policy optimisation (Clarke and Weyant, 2002, p.332; Fischer, 2003)(Jaffe *et al.* 2004). Even absent a 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, instead focusing on the kinds of mitigation policy cost assessments that were just reviewed. 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, 2006). That is, 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 (Vincent *et al.* 2006). However, that same work points out that an even better (welfare improving) policy 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 to successfully correct it in the narrow area of energy R&D. This is true despite our ability to model such results. However, it does open the possibility of portfolios of policies utilizing some of the revenues from emission permit auctions to provide incentives for low-carbon technological innovation. However, it does open the possibility of portfolios of policies utilizing some of the revenues from emission permit auctions to provide incentives for low-carbon technological innovation. Weber *et al.,* (2003), 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 preceding studies that try to 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 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 value of government-sponsored research by itself.

## 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 after 2030. The section concludes by considering wider dimensions of timing and strategy.

### *11.6.1 Structural Trends in the Transition*

Most studies suggest that the focus for potential GHG mitigation shifts over time from energy efficiency improvements to decarbonisation of supply. This is the clear trend in the global scenarios survey in Chapter 3 (Figure 3.3-8), and also in the time-path plots of energy vs carbon intensity changes across the models in the IMCP studies (Edenhofer *et al.*, 2006). It is also true of the national long-term studies surveyed in Chapter 3 (Table 3.10) and of the detailed sectoral assessments of Chapters 4-10. During the early decades (C21$^{st}$-Q1) the majority of global emission savings are associated with end-use savings in buildings and to lesser degree 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 C21$^{st}$-Q2 the focus shifts towards decarbonisation of supplies, through a mix of strategies including CCS and diverse low carbon energy sources.

There are two reasons for this. First, the literature strongly indicates that energy efficiency improvements utilising current technologies give greater potential at lower cost. This is apparent from the sectoral assessments summarised 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 that from energy sector supply switching for costs in the range 0<\$20/tCO$_2$. The second reason is that most models represent 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 their costs come down sufficiently) to make them economic. There is some underlying logic to the fact that some end-use technologies (such as appliances, vehicles) have a capital lifetime much shorter than major supply-side investments; but there are very important caveats to this discussed below.

Hence, for analysis of transitions during C21$^{st}$-Q2, for stabilization across Table 3.5 categories B (420-490ppm $CO_2$) and C (490-570ppmv $CO_2$), most of the relevant modelling literature emphasises energy supply, and other sectors, e.g. forestry, in which mitigation potentials are dominated by long-lifetime, medium-cost cost options.

### *11.6.2 Carbon Prices and Macroeconomic Costs in Transitions*

Many analyses throughout this report emphasise 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, to offer rewards to low carbon innovation, and also potentially to reward sequestration. Most of the regulatory and R&D measures are sector specific and are discussed in the respective sectoral chapters, and 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 consequent changes that would be delivered by equivalent carbon prices. These have their primary effect in reducing $CO_2$ emissions and other GHG missions in the multigas studies. The levels and trends in these prices are crucial to the transition processes. The macroeconomic cost measure is generally GDP or gross marketed world output, without including valuations of non-market environmental costs and benefits.

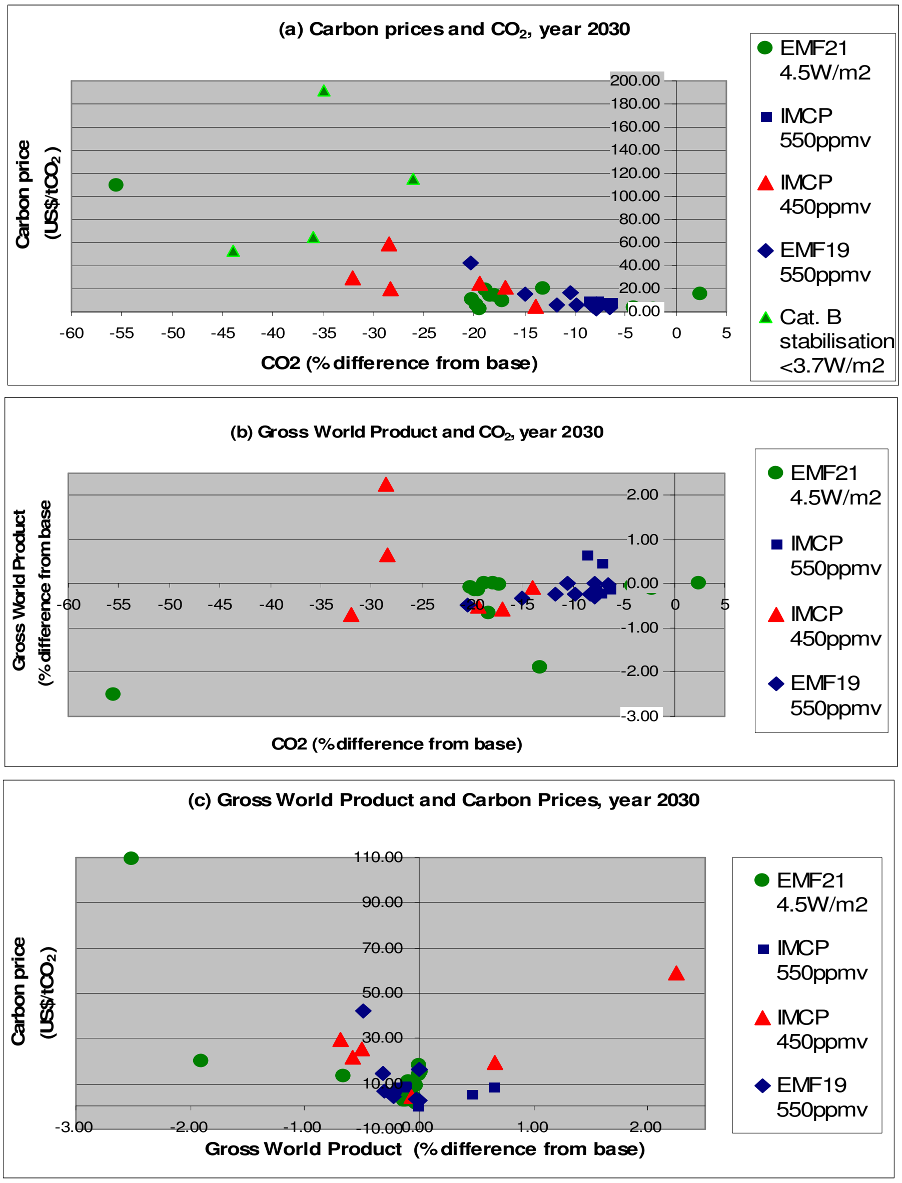


***Figure 11.7****: Year 2030 estimated carbon prices and gross-world-product costs of various stabilisation targets*

*Notes: Figure 11.7(a) shows estimates of the carbon prices required and the outcome for* $CO_2$ *reductions for stabilisation at 4 different levels: EMF21 radiative forcing at 4.5* $W/m^2$ *(multigas); IMCP at 550 and 450ppmv (*$CO_2$ *only with induced technological change); EMF19 at 550ppmv (*$CO_2$ *only with induced technological change); and Category B stabilisation targets (Table 3.5 multigas). Figure 11.7(b) shows the corresponding effects on gross world product where available. Figure 11.7(c) shows the carbon price plotted against the change in gross world product. Note that prices and outputs are on various definitions, so the figures are indicative only.*

*All prices in 1990US$. The EMF and IMCP results shown exclude incomplete sets and the IMCP results exclude those from 2 experimental/partial studies.*

*Sources: (Kainuma et al., 2006, Edenhofer et al., 2006, Table 3.17, Weyant, 2004)*

Figure 11.7 summarises 2030 data from models brought together in the EMF and IMCP studies, and the IEA (2006) study of global emissions to 2050. The figure is is 3 parts, showing the carbon prices by 2030, typically on a rising trend, and their effects on $CO_2$ emissions, the associated effects on gross world output, and the carbon prices shown against to output costs. The results are discussed in terms of pathways towards the mid-ranges of C and B stabilization categories.

**Category C:** The 'optimal' trajectory in most models towards stabilization at $4.5W/m^2$, typically c.550ppm$CO_2$-only requires abatement at less than 20% by 2030 in most of the models, with correspondingly low carbon prices and costs of less than 0.5% global GDP. Most models in the EMF-21 multigas studies for $4.5W/m^2$ suggest a carbon price by 2030 in the range \$10-20/t$CO_2$ (about US\$40-75/tC). The average carbon price in the nearest equivalent (550ppm$CO_2$-only) runs of models with induced technological change in EMF-19 (average \$12/t$CO_2$) and the IMCP studies (\$7/t$CO_2$) tend to be slightly lower, particularly the latter.

**Category B:** The mean carbon price by 2030 across IMCP results for 450ppm $CO_2$-only as shown is \$27/t$CO_2$ (about US\$100/tC); the four models in EMF-21 that report for broadly similar levels all give much higher prices. This may reflect the impact of endogenous technological change, which is greater under more stringent constraints. The carbon prices across all the studies in this category fall within the range \$20-60/t$CO_2$ with two higher costs estimates at 120 and 190 US\$/t$CO_2$. Note also that carbon prices rising, sharply for some of the higher numbers, from lower levels in 2020. Thus, most evidence indicates that the \$20-50/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 B levels. The corresponding $CO_2$ reduction by 2030 is 15-45% relative to baseline (which itself is uncertain and affected by other measures).

Figures 11.7 (b) and (c) show how the carbon prices affect global GDP in the models. The relationship is varied, and three models in particular stand out as radically different from others. For $CO_2$ abatement below 35% and excluding these outliers, the GDP impact by 2030 of the trajectories for stabilization is less than 0.5% GDP for category C, and less than 1.0% GDP for category B; a couple of models in the IMCP predict GDP gains. If the baselines or targets are such as to require 40-60% reductions in $CO_2$ by 2030, many studies expect the costs to be above 1% GDP (see Section 3.3.5.3). 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 above), the use of revenues from permits and taxes (see 11.4 above), and capital stock and inertia (considered below) (Fischer and Morgenstern, 2006, Barker *et al.*, 2006).

Trends in carbon prices

The subsequent time trend of carbon prices 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, increase carbon prices at about 5.5%/yr and over 6%/yr constant across the entire period, so that carbon prices roughly treble over the period 2030-2050, and each subsequent two decades. Two models in the IMCP studies also display constant, much lower growth rates that vary with the stabilization constraint. However most but not all models with endogenous technical change have rates of carbon price increase that decline over time, and a couple actually reduce carbon prices as technological systems mature. The rates of change frequently do not depend much on the stabilization target, which is reached by adjusting the starting carbon price instead.

#### 11.6.2.1 Links with sectoral & technology analyses

The detailed literature on the transition at a global level is limited and the extent of decarbonisation depends upon the baseline and the carbon price. A major study by the IEA (2006) explores a 'MAP' scenario, which returns $CO_2$ emissions by 2050 roughly to 2005 levels (about 500ppm$CO_2$only or a little below), with carbon prices rising to 25 US$/t$CO_2$ by 2030 and then remain fixed. Interestingly, some other models with detailed energy sectors display periods of relatively stable carbon prices with stable or declining emissions.[7] The IEA study emphasises the combination of end-use efficiency in buildings, industry and transport, together with decarbonisation of power generation; by 2050 the power sector is over 50% non-fossil generation, with half of the remainder being coal plant with CCS. In other global studies that report sectoral results, the power sector still dominates emission savings in the Category C scenarios (e.g. Table 3.16). The analysis of Chapter 4 reinforces the view that price levels in the range 20-50 US$/t$CO_2$ are sufficient to make both CCS and a diversity of zero-carbon power generation technologies economic on a global scale.

In Category B scenarios, there is more potential in the transport sector (at higher cost), partly because several of the low carbon transport technologies depend on 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 regarding the associated net costs. 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 element of scale economy / learning-by-doing, therefore, prices maintained at higher levels largely decarbonise the power sector over a period of decades. Some of the models display a second period of similar behaviour, later and at higher prices, as fuel cell-based transport matures and diffuses.

#### 11.6.2.2 Price steps towards *stabilization.*

As emphasised in the final section of Chapter 3, decisions can be revised in the light of evolving knowledge. The sectoral and multi-gas studies indicate that substantial emission savings are still available at low cost (< 20 US$/t$CO_2$), particularly from buildings, agriculture, and end-use efficiencies in a number of sectors; for these reasons many governments are already well embarked upon policies to exploit these low cost opportunities. For the next big step, the combined evidence from all these studies as discussed suggests that increasing and broadening carbon prices - to achieve global levels in the range 20-50 US$/t$CO_2$ (US$75-185/tC) - would be sufficient to largely decarbonise the world's electricity systems, and also make a large impact on deforestation, and a range of industrial, emissions.[8] For comparison, prices in the EU ETS during 2005 were in the middle of this range, at 20-30 €/t$CO_2$. In terms of the "wedges" approach, it implies that such prices levels can deliver sufficient and diverse "wedges" of emission reductions to keep or return global emissions to present levels. The literature thus suggests medium to high confidence that if stable

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[7] Specifically, the GET-LFL 450ppmCO2 run has a peak in carbon prices at 135$/tC in 2020 followed by 2-3 decades of slight decline; the DNE21+ 450ppmCO2 run model rises sharply to about $110/tC in 2020 followed by slow increase for a decade, then a rise to $235/tC in 2040 followed by slow increases out to 2070. See Hedenus, Azar and Lindgren (2006) and Sano *et al.*(2006) respectively. The MIT-EPPA model (McFarland *et al.*, 2004) also shows strong impact of decarbonisation in the power sector, sufficient to stabilise global CO2 emissions from about 2010-2040, with a carbon price that rises from $50-200/tC over this period. An important contribution in this is from gas power generation, including gas with CCS.

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

and predictable carbon prices of 20-50 US$/t$CO_2$ (US$75-185/tC) were to be reached globally by the second quarter of this century (i.e. by 2020-2030), and this were supported by appropriate other measures relating to innovation (discussed below), and efficiency and non-$CO_2$ gases (discussed in the sector chapters), the resulting emissions pathway to 2050 could enable stabilization within category B levels.

The implication of the theoretical discourse about ‘act-then-learn-then-act’ decision-making under uncertainty (Chapter 3), is that these deeper uncertainties need not impede the steps that over the next few decades can ‘keep the window open’ for stabilization in Category B levels, by at least ensuring that global emissions return to present levels before mid Century. Achieving such trends - and opening the window for additional post 2050 action - does however involve a number of additional considerations, to which we now turn.

### *11.6.3 Innovation for Second Quarter-century Transitions*

Some of the technologies required to deliver ongoing emission reductions out to 2050 are already quite well developed, but others (such as CCS) are not (see sector chapters). Deeper emission reductions will get more and more difficult over time without accelerated innovation that brings down the cost, and increases the diversity, of low-carbon options. Achieving the mitigation scenarios indicated thus requires adequate advance in a range of relevant low-carbon-technology-based industries (Weyant et al., 2004; IEA, 2006). Chapter 2 has laid out the basic principles of low-carbon innovation and Chapter 3 the long term role of technologies in stabilization scenarios, whilst the sectoral chapters have discussed the specific technologies. Earlier sections of this chapter discuss modelling of endogenous technological change. This section briefly assesses the insights applied to innovation relevant to second-quarter century transitions.

The conceptual relationship between such innovation investments and measures around carbon pricing is sketched in Figure 11.8. 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 decline, and market scale can grow. A rising carbon price brings forward the date at which they become competitive (indeed many such technologies, like CCS, would never become competitive without carbon pricing). The more quickly that carbon prices rise, the sooner such technologies would become competitive and the greater the overall economic returns to the initial learning investment.

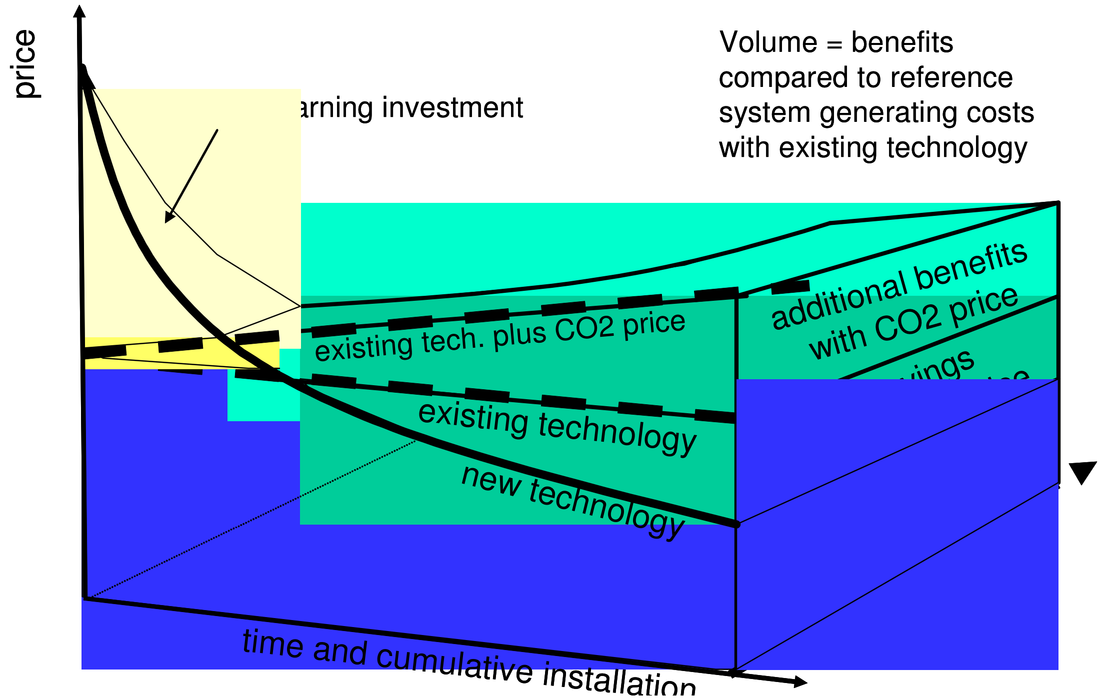

*Figure 11.8: Relationship between learning investments and carbon prices*
*Notes: The Figure illustrates cost relationships for a new low-carbon technology as experience and scale build over time. Initially it is characterized by relatively high present cost and very small market share and requires a high unit rate of 'learning investment'. With growing scale and learning, its costs move towards established, higher-carbon sources, whose costs may also be declining but more slowly. Growing carbon prices over time bring forward the date at which the new technology may be competitive without additional support, and may greatly magnify the economic returns to the initial learning investment.*

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

However the literature equally emphasises that carbon pricing on its own 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) emphasises the interaction of the environmental and the 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. Thus the literature broadly agrees that whilst emission reduction (including pricing) mechanisms are a necessary component for delivering such innovation, they are not sufficient: efficient innovation requires more.

This underlines the complexity of measures required to drive adequate innovation. Based on four general lessons from US technology policy, Alic, Mowery and Rubin (2003) derive various specific conclusions for action[9] divided into direct R&D funding, support for deployment, and support for

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[9] 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 realised 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;

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) sets climate technology policy in the wider experience of US, European and IEA technology programmes and present initiatives, and discusses explicitly the international dimensions associated with globalisation, export credit, diffusion, standards and explicit technology negotiations, whilst Grubb (2005) 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.

The common theme in all these studies is the need for multiple and mutually supporting policies that combine technology push and pull forces, across the various stages of the 'innovation chain', so as to foster more effective innovation and more rapid diffusion of low carbon technologies, nationally and internationally. Most also emphasise the need for feedbacks that enable policy to learn from experience and experimentation - utilising 'learning by doing' in the process of policy development itself.

### *11.6.4 Capital Stock and Inertia Determinants of Second-Quarter Transitions*

The scope for change, and the rate of transition, will be constrained by the inertia of the relevant systems, in which established capital stock plays a large part. 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 thus a central consideration.

The timescales of stock turnover vary enormously between different economic sectors, but appear very long for most greenhouse-gas emitting sectors. Typical investment timescales are several decades for forestry, coal mining and transporting facilities, oil & gas production, refineries, and power generation. On the demand side, observed timescales for typical industrial stock using energy are estimated at decades to a century (Worrel and Biermans, 2002); see Table 11.19. The timescales 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.

***Table 11.19:*** *Observed retirement rates and lifetimes of major GHG-related capital stock.*
Source: Worrel and Biermans (2002)

| | Retirement rate | Average lifetime |
|---|---|---|
| | rate %/yr | (years) |
| Agriculture | 2.0 | 50 |
| Mining | 2.0 | 50 |

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(iii) Technology learning is the essential step that paces adoption and diffusion; (iv) Technology innovation is a highly uncertain process.

| | | |
|---|---|---|
| Construction | 2.0 | 50 |
| Food | 1.7 | 59 |
| Paper | 2.3 | 43 |
| Bulk chemicals | 2.3 | 43 |
| Glass | 1.3 | 77 |
| Cement | 1.2 | 50 |
| | | |
| Steel | | |
| Basic oxygen furnaces | 1.0 | 100 |
| Electric arc furnaces | 1.5 | 67 |
| Coke ovens | 1.5 | 67 |
| Other steel | 2.9 | 34 |
| | | |
| Primary aluminium | 2.1 | 48 |
| Metals-based durables | 1.5 | 67 |
| Other manufacturing | 2.3 | 43 |

Moreover, Lempert and Hart (2002) caution against overly simplistic interpretations of nameplate lifetimes, emphasising 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 decarbonisation. 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 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). 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 of the timescales 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 timescales - 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 (HaDuong et al, 1997). In the context of stabilization at 550ppm $CO_2$, van Vuuren *et al.* (2004) find unambiguously that higher inertia in the energy system brings forward mitigation[10].

However beyond a certain point, inertia can also dramatically increase the cost of stabilization, particularly when infrastructure contraints 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 trebling each decade after, 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 450ppm$CO_2$ stabilization, since much of

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[10] Specifically, including inertia “results in a 10% reduction of global emissions after 5 years and 35% reduction after 30 years”.

this stock then has to be retired in subsequent decades to meet the constraint. This general pattern contrasts sharply with some other studies, such the MIT study (McFarland *et al.*, 2004) that displays an opposite time profile, based partly upon rapid deployment of natural gas plant, including with CCS. Hourcade *et al.* (2006) also estimate 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 choices avoids this squeeze and allows for lower costs of 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, organisational, 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 decarbonise new investments. Shrestha *et al.*(2004) illustrate how the CDM could substantially affect power sector development in three Asian countries. They find that by 2025 the structure of power sector in all would be radically different depending upon the value of Certified Emission Reduction units. Without CERs, by 2025 the share of coal in power generation would be 46%, 78% and 85% in Vietnam, Sir Lanka and Thailand respectively. With a CER price of $US20/tCO$_2$ from 2006 onwards, the share of coal would drop to 18%, 0% and 45% respectively across the three countries by 2025. Natural gas, and to a lesser extent renewables, oil and electricity imports, are the main beneficiaries. This 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.

At a global scale, van Vurren (2004) presents a systematic set of results on effects of different time profiles of carbon prices, in studies that combine representation of inertia and induced innovation. A carbon price that rises linearly to US$82/tCO$_2$ by 2030, reduces emission by 2030 by 40% if the tax were introduced in 2020 and ramped up sharply, but by 55% if it was introduced in 2000 and increased more slowly. They do not set out the impact on subsequent trajectories, but clearly the capital stock endowment differs substantially.

At a more detailed level, such choices are reflected in the scenarios of the International Energy Agency. The IEA (2004) estimates that about US$16tr will be invested in energy supplies up to 2030, about US$10tr of this in the power sector, divided roughly equally between industrialised and developing countries. The more recent IEA 'Map' analysis (IEA, 2006), returning emissions to 2005 levels by 2050 as discussed above underlines the impact of switching investment from more to less carbon intensive paths, although it assumes that carbon prices to do not come in until 2015. Total 'learning investments' across renewables, nuclear and CCS are projected of $7.9tr of which $4.5tr is offset directly by the reduced investment required in fossil-fuel power plants, and most of the rest is offset by reduced need for transmission and distribution investment arising from the increased energy efficiency. The net additional cost for the MAP scenario is only $100bn. The IEA studies collectively emphasise 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.

### *11.6.5 Strategic decision-making in the context of uncertainties, irreversibilities, and intergenerational impacts*

Another strand of literature relates to “transition analysis” emphasising the role of uncertainty, learning and irreversibilities in decision-making, and the implications of this for mitigation investment and pathways.

The literature includes various theoretical models on the implications of irreversibility. Building on a more generalised literature about irreversibility, Ulph (1997) concluded that the combined implications of learning and irreversibility regarding damages were ambiguous, but ‘if discount rates are low and there is considerable uncertainty about future damages, modelling information acquisition and irreversibility could make a significant difference to policy advice’ - the direction of the change depending on the specific assumptions. The model of Pindyck (2000) finds that greater uncertainty always leads to greater delay, but this is based on asymmetric treatment of carbon and non-carbon intensive investments, assuming only the latter to be irreversible.[11]

If the inertia/irreversibility characteristics of more and less carbon-intensive investments are similar, the net influence is the irreversibility of the stock of GHGs and resulting climate damages. The general result is then that greater irreversibility in the context of uncertainties increases required mitigation, but to an extent that declines with the rate of learning. In particular, rapid resolution of uncertainties about the severity of climate damages would greatly reduce the impact of their irreversibility. Kelly and Kolstad (2001) conclude that learning is likely to be slow - many decades; see also for example IPCC AR4 WGI Chapter 10.5, and WGII Chapter 19.3. This would tend strengthen the influence of irreversibility effects.

Since the initial studies of global ‘hedging’ strategies set out in the TAR, the major addition to the literature appears to be that of Mori (2006). Using the MARIA model he analyses optimal strategies to limit global temperature increase to 2.5deg.C under uncertainty about climate sensitivity across the range 1.5 - 4.5 deg.C per doubling of $CO_2$ equivalent. When there is no uncertainty, only the above-average sensitivities require significant mitigation and carbon prices in the second quarter century. In the context of uncertainty, however, carbon prices rise 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.

Shue (2005) takes an entirely different and qualitative ethical approach focused on inter-generational responsibilities in relation to the transition away from fossil fuels. He asserts ‘two reasons why a failure to act is worse than an unfair shirking of responsibility - that delay is likely to magnify severity (to make the worst worse) and that historical choices can be irreversible’.

Long-term uncertainty also has implications for instrument design. Building upon classical economic literature on the topic, Philibert (2004) proposes that an efficient approach may be to set a long term goal (and/or steps towards this) that are made subject to a ‘price cap’ on the realized cost of delivering such emission reductions.

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[11] ‘Policy adoption involves a sunk cost associated with reduction in the entire emissions trajectory, whereas inaction .. only involves continued emissions over that interval’.

### *11.6.6 Some Generic Features Of Long-Term National Studies*

Finally, relevant to the understanding of low-carbon transitions for the first half of this Century are 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. Some quantitative findings of some long-term national modelling studies have been summarized in Chapter 3, and some shorter term studies earlier in this chapter[12]. Additional studies of long-term mitigation in developing countries are beginning to emerge (eg. Shukla 2006, Jiang 2006). The range and number of national analyses, scenarios and strategies devoted towards mitigation targets is beyond the scope of this section but in general they point towards 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 actions 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 incentive 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 Importance and Nature of Spillovers*

Spillover effects of mitigation in a cross-sectoral perspective are the effects of mitigation policies and measures in one country or group of countries on sectors in other countries. (Intergenerational 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 of 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, with an added complication that the effects may be displaced over time. The measurement of the effects is also complicated 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. Whilst much of the literature recognises the existence of spillover effects, uncertainty and disagreement over time scale, cost, technology development, modelling approaches, policy and investment pathways lead to uncertainty about their impacts and in consequence the overall mitigation potentials.

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[12] In addition to some of the specific economy-modeling studies referred to in the previous sections as indicated, strategic national studies written up in the academic literature include the Dutch COOL project (Terriers *et al.*(2005)), and analysis for long-term targets in UK (Johnston et al, 2005; Gross *et al.*, 2005), Japan (Masui *et al*, 2006).

The same spillover effect will be seen differently depending on viewpoint. Differences between regions and nations in many aspects imply differing and perhaps contradictory views toward the policies of mitigation 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 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 economies may not be completely relevant for the economies of developing countries. "The technological profiles and know-how and know-why in developing economies could deter realizing the technical mitigation potential of different options." (Shukla *et al.*, 2000).

Some researchers, using general equilibrium models, (e.g. Babiker, 2005) conclude that spillover, via carbon leakage, under certain assumptions will render mitigation action ineffective or worse if it is confined to Annex I countries. Other researchers taking a different view (e.g. Grubb *et al.*, 2002a; Sijm *et al.*, 2004) argue that spillovers from Annex I action, via induced technological change, could have substantial effects on sustainable development, with emissions intensities of developing countries at 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. In the modelling of spillovers through international trade, researchers rely on approaches (e.g. bottom-up or top-down), assumptions (perfect versus imperfect or "Armington" substitution) and estimates (substitution parameters), whose signs and magnitudes are disputed. Many of the models used for estimating costs of mitigation focus on substitution effects and set aside the induced development and diffusion of technologies, as well as information, policy and political spillovers.

### *11.7.2 Carbon Leakage*

Carbon leakage is measured by the increase in $CO_2$ emissions outside the countries taking domestic mitigation action divided by the reduction in the emissions of these countries. The SAR reported a high range of variation in leakage rates resulting from mitigation measures in OECD countries from close to zero to 70%. The TAR reported a narrowing of the range to 5% - 20% but noted that these estimates come from models with similar treatment and assumptions, and that they do not necessarily reflect more widespread agreement. The TAR also considered spillover through the improvement in performance or reduction in cost of low-carbon technologies.

Carbon leakage pertains to the overall change in emissions. It has been demonstrated that carbon leakage due to a fall in fossil fuel prices (discussed in section 11.7.5 below) that comes as a result of mitigation policies, for example, may lead to reallocation of production to regions with less stringent mitigation rules (or with no rules at all), leading to higher emissions. 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 less or no constraint, due to spillover of learning (discussed in section 11.7.6). Since the TAR the literature has extended earlier equilibrium analysis to include effects of trade liberalisation and increasing returns in energy-intensive industries; and a new empirical literature has developed. The literature on carbon leakage since the TAR has introduced a new dimension to the analysis of the subject, namely the potential carbon leakage from projects intended for developing countries to help them reduce carbon emissions, e.g. (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 1997 Kyoto proposal

Paltsev (2001) uses a static global equilibrium model GTAP-EG to analyse the effects of the 1997 proposed Kyoto Protocol. He reports a leakage rate of 10.5%, within sensitivity 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 contribute the most (20% and 16% respectively), with the EU being the largest regional source (41% of total leakage). The highest bilateral leakage is from EU to China (over 10% of the total). Kuik and Gerlagh (2003) using a similar GTAP-E model conclude that for Annex I Kyoto-style action the major reason for the 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, presenting 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, which depend on the assumptions adopted of between 25% to 130%. The main reasons for the higher estimates are the inclusion of a treatment 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 actions in one region lead to more global GHG emissions rather than less.

Significant carbon leakage arises when internationally tradeable energy-intensive production moves abroad to non-abating regions, frequently referred to as a competitiveness concern. In industrialised 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 (e.g. through derogation, exemption or protection for such sectors).

#### 11.7.2.2 Sectoral analysis of carbon leakage

Sijm *et al.* (2004) provide an in-depth literature review and assessment of the potential effects of Annex I mitigation associated with the EU emission trading scheme (ETS) on carbon leakage, especially from a technological perspective, and especially in developing countries. Technological spillovers are considered in section 11.7.6 below. In the empirical analysis of effects in energy-intensive industries there are many other factors besides the price competitiveness considered in the modelling studies reporting high leakage rates. 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 the simple indicator of carbon leakage is insufficient for policy making. Szabo *et al.* (2006) report production leakage estimates of 29% for cement with an EU ETS allowance price of euro40/tCO2 using a detailed model of the world industry. Leakage rates rise the higher the allowance price. More generally, Reinaud (2005) surveys estimates of leakage for energy-intensive industries (steel, cement, newsprint and aluminium) with the EU ETS. She comes to a similar conclusion 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 CDM and compensation*

The Kyoto mechanisms may also have spillover effects, offsetting their additionality. Gundimeda (2004) considers how the 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 result in sustainable development of the local people, three important criteria should be satisfied: (1) Integrating the energy substitution possibilities in the objectives of carbon sequestration; (2) Management of the [common] … lands by the rural poor through proper design of the rules for 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 ... 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 emission trading (ET)) using a general equilibrium model WIAGEM, with Kyoto-style (with USA) action continuing until 2050. The study shows the full welfare effect (% difference from business as usual) in 2050 divided into effects of domestic action, competitiveness and spillovers. Notable are the very small effects of the mechanisms on welfare: at most, as an outlier, there is a 0.7% increase for countries in transition (REC) for emissions trading and an 0.1% decrease for the EU15 for joint implementation. The CDM is seen mostly to improve welfare 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 there were possibilities of the CDM leading to more technological development, 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.

Bohringer 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 an estimated compensation of $0.7 billion annually to offsets the adverse impacts on these regions and the EU should pay the same amount to the US to account for the positive spillover.

### *11.7.4 Impact on Competitiveness (trade, investment, labour, sector structure)*

The international competitiveness of economies and sectors is affected by mitigation actions (see surveys by Boltho (1996), Adams (1997) and Barker and Köhler (1998)). In the long run, exchange rates change to compensate for persistent loss of national competitiveness, but this is a general effect and particular sectors can lose or gain competitiveness. In the short run, higher costs of fossil fuels lead to a loss in sectoral price competitiveness especially in energy-intensive industries. The effects of domestic mitigation actions on a region's international competitiveness are divided in 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 6.6.3 above). Zhang and Baranzini (2004) have reviewed empirical studies of the effects of Annex I action on international competitiveness. The study by Baron and ECONEnergy (1997) for the Annex I expert group on the UNFCCC is typical. They report a static analysis of the cost increases from a tax of $100/tC 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 all country-sectors studied, with higher cost increase in Canada (all 4 sectors), Australia (both metal sectors) and Belgium (iron and steel). They conclude that "empirical studies on existing carbon/energy taxes seem to indicate that competitive losses are not significant" supporting 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).

However, actions 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 caused by spillover effects 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 considered by the receiving countries as Foreign Direct Investment (FDI). Different market regulations and the flow of goods and services as dictated 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).

FDI may induce a negative impact on the local labour market due to cost minimization and specialization. As businesses re-locate as a results of mitigation polices, wage inflexibility can result due to a mismatch between labour demand and labour supply causing involuntary unemployment to increase. To satisfy the requirement for specialized skills in the labour market, more investment in training and a shift to different disciplines will be required in order to bring the labour market closer to meeting business needs. Employees with the required knowledge will benefit the most as wages increase, but increasing wages may tend to cause employers to hire fewer workers. FDI may increase demand for skilled workers at the expense of unskilled workers. Trade, investment and labour market development within and between regions and the effects on different mitigation policies is not often discussed in the literature. While international trade is seen as a contributor (through economic growth and use of fossil fuels) as well as a remedy for climate change (through transmission of low-carbon technologies), fair competition in international trade may be affected by the proposed measures for dealing with it. Measuring the impact and effects, both positive and negative, of the set of policy changes proposed to mitigate climate change as well as their spillover effects is a major issue[13] (Bernstein *et al.*, 1999).

### *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 affects the others is through its effect on world fossil-fuel 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 fossil-fuel producer's response, oil, gas or coal prices may fall, leading to loss of revenues by the producers, and lower costs of imports for the consumers. Three distinct spillover effects are identified for non-mitigating countries. First, income for fossil-fuel producers will decline as the quantity sold is reduced, causing welfare losses and a high level of 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 large global markets in biofuels (Chapter 8 above).

Effects of Annex I action reported in the TAR

The TAR reviewed studies of Annex I action in the form of a carbon tax or emission trading schemes, using CGE models with no induced technological change. The TAR (pp 541-6) reported that for Kyoto-abatement in Annex I, "it was universally found that most non-Annex I economies that suffered welfare losses under uniform independent abatement also suffered smaller welfare losses under emission trading" (p. 542). The magnitude of these losses is reduced under less stringent Kyoto targets. 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 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. Analysis pertaining to the group of oil-exporting non-Annex I countries report costs differently, including inter alia, reductions in projected oil revenues. Emission 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 emission trading in 2010. The study reporting the highest costs shows reduction of 25% of projected oil revenues with no emission trading, and 13% of projected oil revenues with Annex B emission trading in 2010 (WGIII, TS, 2001, p.60).

#### 11.7.5.1 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 effects on regions' GDP and welfare are mixed. Some studies point at gains by Annex I

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[13] "Changes in investment are also affected by decisions to reallocate consumption over time, financed in part by changes in domestic saving and partly by changes in international lending. The direction of capital flows will be determined by changes in savings decisions in the different regions and by the demand for capital to change the shares of energy-intensive industries in national output."

countries and losses to the developing countries, while others note losses in both with varying magnitudes depending on differing assumptions in the models. Studies that consider welfare gains/losses and international trade in Annex I countries also have mixed results even if subsidies plus incentives and ancillary benefits are taken into account (Bernstein *et al.*, 1999; Pershing, 2000; Barnett *et al.*, 2004).

Barnett *et al.* (2004) quote the highest of the modelling costs for OPEC (Pershing, 2000) from implementing the Kyoto Protocol for action in all Annex I countries as the 13% loss of oil revenues in the GCubed model (also noted in the TAR). They 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. The scenario assumes 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 decreases, but not below levels in 2005, so that OPEC's market power will not fall from current levels. The scenarios show that OPEC can maintain the projected baseline revenues by restricting production by some 26% (Annex B country action is restricting consumption to match), giving an oil price of US$(2000)22.7/bbl compared to US$(2000)19.4/bbl in the baseline by 2010. These prices compare to those in 2005 over $60/bbl.

However, OPEC's market power is uncertain. OPEC's World Energy Model has been solved assuming that OPEC production remains at baseline levels in the scenarios, so over-supplying the market, since oil demand is reduced. This leads to an estimate of OPEC losses of $63bn a year or about 10% of GDP compared with 2% if supply is restricted 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 acted with OPEC. The conclusion was that OPEC losses would be substantially reduced. Another interesting feature of these results is that the losses as a % of 1999 GDP vary substantially across economies, between 3.3% for Qatar to 0.07% for Indonesia by 2010.

World Energy Outlook (IEA 2005) reports the impacts of additional policies under consideration in the OECD, China, India, Brazil, Egypt and Iran to improve energy efficiencies, particularly in transportation. The policies are justified as contributing to energy security and GHG mitigation, as well as being justified as improving market efficiency through removing barriers and improving information. They reduce $CO_2$ by 16% below reference case by 2030, through reduced use of coal (23% less), oil and gas (10% less), and increased use of nuclear (14% more) and non-hydro, non-biomass renewables (27% more) (p. 270). *Average* oil prices over the whole period 2004-2030 are reduced from 39 US$(2004)/bbl in the reference case to 33 US$(2004)/bbl with the energy efficiency policies, yielding substantial net benefits to oil consumers. The IEA reports cumulative oil and gas revenues for Middle East and North African exporters 2005-2030 as $(2004)12,000bn, reduced by 21% by the additional policies (p. 276), but production for the region continues to rise by more than 50% 2004-2050 (p. 252).

No estimates of the effects on global GDP are given by the IEA, but it may well be higher. No indication is given of the scale of rebound effects assumed for the policies or of any complementary policies to raise the price of carbon. Finally no indication is given as to the appropriate and efficient scale of the policies, an important issue for GHG mitigation since a scaling up may reduce global $CO_2$ even more than the 16% of the study at net benefit. However, the policies under consideration do not necessarily target GHGs, so a more targeted portfolio would presumably reduce GHGs even more.

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 GDP gains of 0.2 to 0.6%. 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 oil-producing countries than on the countries who are taking the abatement measures.

### *11.7.6 Technological Spillovers*

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 changed 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 have 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 is 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 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.

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). The use of hydrogen-fuel-based energy as a new $CO_2$ reduction technology faces similar challenges in addition to contributing to the environmental problem. (Alharthi and Alfehaid, 2005). An additional issue is that technology sharing by the fossil-fuel energy suppliers has been severely limited to date, probably due to the industrial organisation of coal, oil and gas production, which is dominated by a few large private and state companies. Unlike for example new technologies in information technologies, which quickly becomes industry standard, newly developed energy-related technology providing competitive advantage is generally slowly made available to competitors. Technologies reducing $CO_2$ emissions in the electricity sectors, on the other hand, may be more accessible. Modelling of the spillovers and evolution of technologies as well as structural changes in the management of firms however, require a better understanding of knowledge production and the knowledge transfer process within and between industries, the role and efficiency of transfer institutions such as universities, technology-transfer centres and consulting 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 the levels of activities, which themselves are driven by a wide range of non-climate related policy interests. These include, inter alia, 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. Thus, there are common drivers behind policies addressing economic development and poverty alleviation, employment, energy security, local environmental protection on the one side 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 simultaneously advance both. 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 policies and energy security concerns.

### *11.8.1 Interactions 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 scale. Since the TAR, a wealth of new literature has pointed out that capturing synergies and avoiding trade-offs in 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 mismatches of the temporal and spatial scales between air pollution control and climate change mitigation. Benefits from reduced air pollution occur in the short- to medium-term and close to the places where measures are taken, while climate impacts are 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 for industrialized and developing countries a variety of co-benefits of greenhouse gas mitigation on air pollution. Valued with standard economic techniques, in many cases the health and environmental benefits make up substantial fractions of the direct mitigation costs. More recent studies have found for decarbonization strategies significant direct cost savings from 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, e.g., different baseline emissions projections, air quality modelling techniques, health impacts assessments, valuation methods, etc. These differences in methods, together with the scarcity of data, are a major source of uncertainties in the estimates of co-benefits.

While the recent literature provides new insights into individual co-benefits (e.g., on health, agriculture, ecosystems, cost savings, etc.), it is still challenging to derive a complete picture of total co-benefits.

#### 11.8.1.2 Co-benefits for Human Health

The burning of fossil fuels is linked to both climate change and air pollution, therefore 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. Epidemiological studies have identified consistent associations between human health (mortality and morbidity) and the exposure to fine particulate matter and ground-level ozone, both in industrialized and developing countries (WHO, 2003; HEI, 2004).

Numerous new studies demonstrate significant benefits of carbon mitigation strategies on human health from lower precursor emissions that form particulate matter and ozone in the atmosphere. Most important for human health are primary emissions of particulate matter (PM), sulfur dioxide ($SO_2$) and nitrogen oxides ($NO_x$). 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 11.20). 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 five to 10%. The associated health impacts are substantial, and 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 ten thousand cases of premature deaths that could be annually avoided as a side-effect of moderate $CO_2$ mitigation strategies (Wang and Smith, 1999; Aunan *et al.*, 2003; Aunan *et al.*, 2006; Vennemo *et al.*, 2006) - for China; (Bussolo and O'Connor, 2001) - for India; (Cifuentes *et al.*, 2001; Dessus and O'Connor, 2003; McKinley *et al.*, 2005) - for Latin America). Studies for Europe (Bye *et al.*, 2002; van Vuuren *et al.*, 2006a), North America (Caton and Constable, 2000; Burtraw *et al.*, 2003) and Korea (Han, 2001; Joh *et al.*, 2003) reveal less, but still substantial, health benefits from moderate $CO_2$ mitigation strategies, typically of the order of several thousand cases of premature deaths that could be avoided annually.

***Table 11.20****: Implications for air-quality co-benefits from GHG mitigation studies*

| Authors | Country | Target year | Sector | Delta $CO_2$ emissions | C price US-$/t C | Difference in coal use | Impact on air pollutant emissions | Difference in health impacts | Health benefits US $/t C | Difference in air pollution control costs | Total benefits |
|---|---|---|---|---|---|---|---|---|---|---|---|
| EIA 1998 | US | 2008-2012 | Power sector | -31% | | -77% | | | | | |
| | | 2008-2013 | Power sector | -36% | | -92% | | | | | |
| Burtraw 2003 | US | 2010 | Power sector | | 25 $/t C | | | | 8 $/t C | 4-7 $/t C | |
| Canton 2000 | Canada | 2010 | All sectors | - 9% | | | $SO_2$: -9%<br>$NO_x$: -7%<br>PM: -1% | | 42 $/t C<br>(12-77) | | |
| Wang & Smith 1999 | China | 2020 | Power sector | 15% below BAU | 40 $/t C | | | 4,400-5,200 premature deaths/yr | | | |
| | | 2020 | Domestic sector | 15% below BAU | 5 $/t C | | | 120,000-180,000 premature deaths/yr | | | |
| O'Connor 2003 | China | 2010 | All sources | 15% below BAU | | | | | | | no loss in net welfare |
| Aunan 2004 | Shanxi. China | 2000 | Cogeneration | | -108 $/t C | | | | 117 $/t C | | |
| | | 2000 | Modified boiler design | | -22 $/t C | | | | 86 $/t C | | |
| | | 2000 | Boiler replacement | | -10 $/t C | | | | 117 $/t C | | |
| | | 2000 | Improved boiler management | | 33 $/t C | | | | 117 $/t C | | |
| | | 2000 | Coal washing | | 82 $/t C | | | | 314 $/t C | | |
| | | 2000 | Briquetting | | 98 $/t C | | | | 433 $/t C | | |
| Kan et al., 2004 | Shanghai, China | 2010<br>2020 | All sources | | 200 Yuan/ t $CO_2$ | | | For 2010: 608-5144 For | | | |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 2020: 1189-10462 premature deaths/yr | | | |
| Li | Thailand | | | | | | | | | | -45% lower welfare losses |
| Vennemo et al. 2006 | China | 2008-2012 | Power production, industrial boilers, steel making, cement, chemical industry | 80-236 Mt $CO_2$ annually | 22 USD/tC 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 mill ton $CO_2$) | Avoided deaths: 34-15-75 $/t C; all health effects: 20-160 $/t C | | |
| Morgenstern 2004 | Taiyuan, China | | Phase-out of small boilers | 80% | | | -95% | | 138-642 $/t C | | |
| Bussolo & O'Connor 2001 | India | | All sources | 13-23% below BAU | | | | | | | no welfare loss |
| Joh et al. 2003 | Korea | 2020 | | 5-15% | | | | | 6.8-7.5 $/t C | | |
| Han 2001 | Korea | 2010 | All Sources | -10% | | | $SO_2$: -10%<br>$NO_x$: -9.6%<br>PM: -10% | | 214-277 $/t C | | |
| 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%<br>$NO_x$: 10-15% | | | -10% | |
| Fichtner et al., 2003 | Baden-Wuerttemberg, Germany | | | | | | | | | | |
| Proost et al. (2004) | Belgium | 2010-2030 | All Sources | 7-15% | | | | | | | 30% of mitigation |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | costs |
| Syri et al., 2002 | Finland | 2010 | All Sources | Kyoto compliance | $SO_2$: -10%<br>$NO_x$ : -5%<br>PM: -5% | | | |
| Bye et al. (2002) | Nordic countries | | All sources | 20-30% | | | 35-80 $/t C | -0.4% to -1.2 % of GDP |
| Cifuentes (2001, 2003) | Mexico City, Santiago, Sao Paulo, New York | 2020 | | | | 64,000 premature deaths/yr | | |
| West et al. (2004) | Mexico City | 2010 | 18 GHG measures (mainly transport) | 9% | $PM_{10}$: -1.3%<br>$NO_x$: 1.4 %<br>HC: 3.2 % | | | |
| Mc Kinley *et al.*(2005) | Mexico City | 2020 | 5 mitigation options | 0.8 Mt C/yr (1.1 %) | | 100 premature deaths/yr | | |
| Dessus et al. | Santiago de Chile | 2010 | | 20% below BAU | | | | no welfare loss |

Several authors conducted an economic valuation of these health impacts 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 7 US-$/tC (Burtraw *et al.*, 2003; Joh *et al.*, 2003) up to several hundreds US-$/tC (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 (e.g. $SO_2$ or $NO_x$), while the higher estimates comprise multiple pollutants including fine particulate matter, which has been recently shown to have largest impacts. Differences in mortality evaluation methods and results constitute a substantial source of discrepancy in the estimated value of health impacts 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 strong impact on population exposure (e.g. domestic stoves for heating and cooking, especially in developing countries) can typically have 40 times larger health benefits than a reduction of emissions from centralized facilities with high stacks, e.g., power plants (Wang and Smith, 1999). Mestl *et al.*, (2005) show that the local health benefits from 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 are 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 for a substantial fraction of mitigation costs. Depending on the stringency of the mitigation level, the source sector, the mitigation 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). Especially for developing countries, several of the reviewed studies point out scope for no-regret measures.

Such a potential for developing countries is consistently confirmed by studies applying a general equilibrium modelling approach, which takes into account economic feedbacks within the economy. Bussolo & O'Connor (2001) estimate for 2010 the potential for $CO_2$ mitigation in India without net loss in welfare between 13 and 23% of the emissions of 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 for Chile at 20% compared to 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% and improves welfare for households and cleaner producers.

Analyzing non-$CO_2$ greenhouse gases broadens the scope of climate protection and expands opportunities for synergies with local pollutants, as co-emission of local pollutants and greenhouse gases vary by the type of greenhouse gas considered. 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% beginning 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 $CO_2$.

### 11.8.1.3 Co-benefits for Agricultural Production

While a strong body of literature demonstrates important co-benefits between GHG mitigation and health benefits from improved air quality, less research has addressed 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 earlier been reviewed in USEPA (1996) and EC (1999). Chameides *et al.* (1994) estimate that 10-35% of the world's grain production occurs in locations where ozone exposure may reduce crop yields. Surface ozone levels are sensitive, inter alia, to $NO_x$ and VOC emissions from fossil-fuel-burning power plants, industrial boilers, motor vehicle exhaust, gasoline retail outlets, and N-fertiliser induced soil emission of $NO_x$.

Using an atmospheric ozone formation model and an economic general equilibrium model, Aunan *et al.* (2006) find for a $CO_2$ mitigation strategy in China the monetary benefits from increased agricultural productivity due to lower ground-level ozone to be 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. Without considering agricultural effects, poor rural households experience welfare losses from carbon mitigation even at low levels of abatement. Once agricultural effects are considered, rural households enjoy welfare gains up to a ten percent abatement rate in this study. Thus, 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 decarbonisation strategies from reduced air pollution on **natural ecosystems.** VanVuuren *et al.* (2006a) estimates for Europe that, 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 (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 consider the environmental sensitivities of ecosystems that are affected by the associated air pollution emissions. Similar results have been obtained by Syri *et al.* (2001).

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

### 11.8.1.5 Avoided Air-Pollution Control Costs

As pointed out above, co-benefits from $CO_2$ mitigation on air pollution impacts have been found largest in developing countries, where air pollutants are often emitted without stringent emission control legislation. Most industrialized countries, however, enforce a comprehensive legal framework to safeguard local air quality, which includes 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. In case of source-specific performance standards, fewer plants burning fossil fuels also imply fewer air pollution control devices. If overall emissions in a country are capped, e.g., 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, lower consumption of carbonaceous fuels also reduces the costs for complying with such emission ceilings. This is particularly important, since under such conditions countries can avoid implementing more expensive air pollution control measures. A similar situation applies for 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 will be 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 comparable or in some periods even higher than the total costs of an integrated strategy that also includes $CO_2$ mitigation.

The influence of flexible mechanisms on cost savings has been further explored by van Vuuren *et al.* (2004) for the western European countries. If the Kyoto obligations were implemented through domestic action alone, $CO_2$ mitigation measures for 12 billion €/year would allow savings on air pollution control costs of 6.6 billion €/year. In contrast, if these countries reached compliance through buying permits for 3 billion €/yr from outside and implemented domestic measures for 1 billion €/yr, air pollution control costs would decline by 1.7 billion €/yr in these countries. At the same time, the other European countries selling permits (for 3 billion €/yr) would additionally save 0.5 billion €/yr on their own air pollution control costs due to the additional carbon mitigation measures.

For the United States, a study by EIA (1999) 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 25 US-$/t C carbon tax savings of 4-7 US$/t C from reduced investments in $SO_2$ and $NO_x$ abatement in order to comply with the 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 into mitigation measures. Therefore they add an important component to a comprehensive assessment of the co-benefits of mitigation strategies. While today these cost savings emerge predominantly in industrialized countries with elaborated air quality regulations, they will gain increasing importance also in developing countries as these progressively implement action to achieve sustainable levels of local air quality as well.

### 11.8.1.6 The Need for an Integrated Approach

While the above studies use different methodological approaches, there is general consensus for all analyzed world regions 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, much of the benefits could occur by improving the efficiency of or switching away from traditional use of coal and biomass. Such near-term secondary 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 turned out to be less than current projections show.

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 these 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. Thus, piecemeal regulatory treatment of individual pollutants rather than a comprehensive approach could lead to stranded investments in equipment (e.g., if new conventional air pollutant standards are put in place in advance of carbon dioxide controls at power plants) (Lempert *et al.*, 2002).

Based on 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.

### 11.8.1.7 Co-control of emissions

Co-control of emissions, i.e., 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 GHGes are often emitted by the same sources and hence 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 increased usage of natural gas can address both problems (synergies), while desulphurisation of flue gases reduces sulphur emissions but can - to a limited extent - increase carbon dioxide emissions (tradeoffs). Trade-offs also exist for $NO_x$ control measures for vehicles and nitric acid plants, where it may increase $N_2O$ emissions. 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, de Brink *et al.* (2001) have estimated that abating agricultural emissions of ammonia ($NH_3$) may cause releases of $N_2O$ from this sector up to 15% higher than in the case 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.

#### 11.8.1.8 Methane-ozone

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. Thus, 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).

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 hemispheric scale emissions and are strongly influenced by atmospheric processes involving methane.

Tropospheric ozone, in addition to its health and vegetation effects, is also a potent GHG (*Reference to Working Group 1 here)*. Thus, ozone reductions will not only have 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.

#### 11.8.1.9 Biofuels

Particularly relevant trade-offs have been identified for GHG mitigation strategies that enhance the use of biofuels and diesel. Bio-fuels are considered carbon neutral and thus have been suggested as an important element of decarbonisation strategies. However, their combustion in household devices in 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 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 for health impacts from air pollution in developing countries, adding the highest burden of disease (Smith *et al.*, 2004). In addition to the negative health impacts of biomass combustion, there are concerns about the effectiveness of combustion of biomass in stoves as a climate change mitigation measure due to the impacts of emissions of incomplete combustion products on the radiation balance (Smith *et al.*, 2004).

On the other hand, ethanol and biodiesel can be produced from biomass in medium to large industrial installations with stringent air quality control measures, which would prevent negative health impacts.

#### 11.8.1.10 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 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 the efforts of air quality management. 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 $CO_2$ emissions (Jacobson, 2002).

#### 11.8.1.11 Practical examples of integrated strategies

The realization of co-benefits has moved beyond a notion or an analytical exercise.

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

The European Commission, in its European Climate Change (ECCP) and Clean Air For Europe (CAFE) programs, explored 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, methyl bromide. Some of the alternatives to these products which are used primarily in refrigeration, air-conditioning and for producing insulating foam, have significant GWPs although, in many cases, less than the CFCs and HCFCs. They also can improve the energy efficiency of some equipement and products in which they are used. In order to investigate the linkage 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 (reference).

### *11.8.2 Impacts of GHG Mitigation on Employment and Energy Security*

A number of studies point out that investments into greenhouse gas mitigation could have larger employment impacts than investments into conventional technologies. The German Council for Sustainable Development estimates that more than 2 000 full-time jobs could be created for each million tonnes of oil equivalent that will be saved as a result of measures and/or investments specially taken to improve energy efficiency as compared to investing in energy production (Council for Sustainable Development, 2003) cited in European Commission, 2005). Furthermore, the European Commission (2005) estimates that the suggested 20% saving of present energy consumption in the European Union by 2020 can potentially create directly or indirectly up to one million new jobs in Europe. The net impact on employment in Europe in the manufacturing and construction industries of a one percent annual improvement in energy efficiency - a target proposed and under discussion in the European Union - has been shown to induce a positive effect on total employment (Jeeninga *et al.*, 1999); European Commission, 2003). The effect has been shown to be substantially positive, even after taking into account all direct and indirect macroeconomic factors such as the reduced consumption of energy, impact on energy prices, reduced VAT, etc (European Commission, 2003). The strongest effects are shown to in the area of semi-skilled labour in the buildings trades, which also affords the strongest regional policy effects (Jeeninga *et al.*, 1999)( European Commission, 2003).

For Poland the labour intensity of renewable energy sources has been estimated approximately 10 times higher than for traditional coal power (0.1-0.9 jobs/GWh compared to 0.01 - 0.1 jobs/GWh). Thereby, the governmental targets on renewable energy would create 30,000 new jobs by 2010 (Jeeninga *et al.*, 1999).

Greenhouse gas mitigation has beneficial effects on energy security through increased energy efficiency and renewable utilisation.

### *11.8.3 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 (yet) provide a complete picture that includes all different types of co-benefits that would be needed for a comprehensive assessment. Nevertheless, even the currently quantified co-benefits 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 to simultaneously address all relevant areas. There are practical examples of targeted programs to pinpoint co-benefits and to identify those policy measures that have largest potential for capturing possible synergies.

For low-income countries, giving attention to potential synergies between GHG mitigation and other policy objectives could be even more important than in high-income countries. Presently, climate change policies are often still relatively marginal issues in these countries compared to issues such as poverty eradication, food supply, provision of energy services, employment, transportation and local environmental quality. In this way, an accelerated and sustainable development could become a mutual interest of 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 actions and the effects of mitigation actions on adaptation as identified in Chapters 4 to 10 above and in the literature. The topic of adaptation-mitigation linkage is covered in Chapter 2, section 6, and WG2 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 published literature: some (Barker, 2003; Dessai and Hulme, 2003) analyze mitigation and adaptation linkages as fairly distinctive responses within the context of integrated assessment models; while others (Dang *et al.*, 2003; Klein *et al.*, 2003) have more explicitly addressed the issue of whether and how mitigation and adaptation measures should be more effectively integrated as an overall development response to the threat of climate change.

### *11.9.1 Sectoral Mitigation Actions: Linkages with Climate Change and Adaptation*

#### 11.9.1.1 Energy

Regarding vulnerability of the energy sector, there is a growing recognition that energy supply, particularly at the level of infrastructure, can be seriously impacted by climate change, ranging from extreme events (witness impacts of last year's hurricane season on oil platforms in the Gulf of Mexico, (Easterling *et al.*, 2000)) to warming conditions for permafrost in Canada's and Russia's Arctic that will have a significant impact on the construction of gas and oil pipelines. Significant changes in water levels for hydro projects could also potentially have significant impacts (Nelson *et al.*, 2002). There are also opportunities for synergies between mitigation and adaptation on the question of energy supply, particularly for rural populations. For example, a choice to develop perennial biofuels, such as switch grass, would meet rural energy needs through the use of a crop that would also provide adaptation benefits through its relatively low water supply requirements (Samson *et al.*, 2000). In any case, there is a broad consensus that a decentralized energy system might be more robust to extreme events.

Particular areas that clearly demonstrate linkages in the energy sector include hydro and biomass. In relation to hydro, changes in rainfall patterns/melting of glaciers will clearly have impact on hydro power production and these eventualities clearly need to be taken into account when promoting 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 decreasing communities' ability to adapt to the impacts of climate change, decrease food supply and thereby make it more vulnerable.

#### 11.9.1.2 Transportation

The transportation sector can, in particular instances, be extremely vulnerable to the impacts of climate change, particularly, again as it relates to infrastructural support. For example, in the Arctic areas, seasons are becoming shorter for ice roads that are critical for transporting construction materials to remote villages (Nickels *et al.*, 2005). Decreasing water levels in the Great Lakes and the opening up of the North West Sea passage due to the melting polar cap in the North could both have significant impacts on the shipping industry (Johannsen, 2004). In respect to coastal areas as well, transportation infrastructures, particularly in the areas of public transport, can be vulnerable to extreme events, as could all major infrastructural investments.

#### 11.9.1.3 Commercial and Residential Buildings

While it is clear that the impacts of climate change on commercial and residential buildings could be massive, particularly through extreme events and seal level rise, less appreciated is the large synergies that can exist between adaptation and mitigation. While it had often been a strong consideration in the past, modern architecture rarely takes prevailing climates into consideration, although by design and adaptation to the prospects for climate change, buildings could considerably decrease their energy load (Larsson, 2003). Nevertheless, it is clear that there is a relatively small amount of literature exploring AM linkages for new and existing buildings. For example, more attention needs to be paid to potential conflicts in investment priorities between protecting buildings against the increased risk of flooding versus improving insulation and energy performing systems. Again, a sizeable increase in heat waves in urban centres might increase pressure for the penetration of low cost air conditioners, increasing power demand and $CO_2$ emissions.

#### 11.9.1.4 Industry

For industry it is assumed that they would not be as vulnerable to the impacts of climate since they are usually built with possible extreme conditions in mind, but again there appears to be no explicit consideration of how industry could design its manufacturing and operating process in such a way that by adapting to possible climate change events it can also help to reduce the GHG emissions associated with their operations. (This of course is very industry and region specific.) (Subak, 2000).

#### 11.9.1.5 Agriculture and Forestry

Most of the literature relating to mitigation-adaptation linkages can be found in the discussions around 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 least developed countries: many actions focusing on sustainable natural resource management policies could potentially provide both significant adaptation benefits while also working to provide mitigation benefits, mostly in the form of sequestration activities, that may not easily be measurable or verified. (Gundimeda, 2004; Morlot and Agrawala, 2004; Murdiyarso *et al.*, 2004). Agriculture is, of course, extremely vulnerable, to the impacts of climate change, covering all aspects related to crop land management, particularly on aspects related to water management, as in, for example, rice cultivation. As discussed in the energy section, bioenergy, can of course play a significant role in mitigating global GHG emissions, although full life cycle implications of bioenergy options, including impacts on deforestation and agriculture, needs to be taken into account.

As was the case with agriculture, a number of synergies and trade offs can exist between adaptation and mitigation in the forestry sector, and often times these actions are taken without either adaptation or mitigation being taken into account (Huq and Grubb, 2004). It is also being increasingly recognized that forestry mitigation projects can often carry significant adaptation benefits, particularly in the areas of forest conservation, afforestation and reforestation, biomass energy plantations, agro-forestry, urban forestry. And that many adaptation projects in forestry can carry mitigation benefits, including soil and water conservation, agroforestry and biodiversity conservation.

Large-scale expansion of land-based renewable energy sources is constrained under the Marrakesh Accords[14]. Even so, there may be increased competition for land in many regions with two crucial effects. First, the increased pressure to bring currently non-agricultural areas under cultivation may reduce the area available to natural ecosystems, increase its fragmentation and restrain the natural adaptive capacity. Second, increasing land rents might make agronomically viable adaptation options unprofitable. This mitigation strategy also affects water resources: if applied in water-stressed regions, the drastically increased evapotranspiration exacerbates water shortage and makes coping with climate change impacts more difficult.

An alternative view is that water requirements have been exaggerated (Berndes *et al.*, 2001) and that the productivity of land is as important as its absolute supply: there is no shortage of land (Bot *et al.*, 2000; Moreira, 2005), but of investment in land, which can be remedied by revenues derived from the energy sector (e.g. through the CDM) both to raise land productivity through carbon-sequestering soil improvement and to co-produce food or fibre with bio-mass residuals for conversion to bio-energy products (Greene *et al.*, 2004; Faaij, 2005; Read, 2005; Lehmann *et al.*, 2006; Verchot *et al.*, forthcoming). Recent studies suggest that technological progress in agriculture will outstrip population growth under a variety of SRES scenarios leaving land for bio-energy cropping sufficient, in the most optimistic scenario, to meet all forecast demands for primary energy (Hoogwijk *et al.*, 2005). Bio-diversity, migration trails, etc., may be conserved by appropriate land use planning enforced through conditionality on the CDM derived emissions reduction certificate (Caparros and Jacquemont, 2003; Read, 2006). Thus there may be may be positive effects in other circumstances or offsetting these damages: additional employment in rural areas will raise incomes and reduce migration. Well-designed CDM projects can reduce use of traditional biomass as fuel (Gundimeda, 2004) and replace it with marketable renewable fuels, providing a double benefit. There may be also benefits of some mitigation measures for human health, increasing the overall adaptive capacity of the population and making it less vulnerable to specific climate impacts.

### *11.9.2 Global, National, and Local Level Conflicts and Synergies*

There is a wide recognition that, on a global scale, adaptation and mitigation measures will be required to address the impending challenge of climate change. More specifically, regardless of the mitigation commitments currently taken on by countries, globally, we are on an emissions growth curve that will require adaptation to the impacts (WG2 Chapter 18) or the other. What is not as clearly laid out in the literature is any sense of what a reasonable portfolio of adaptation and mitigation broad policies might look like.

As a result, 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 be battling one another over a limited amount of funds available in a country to address climate change, with analysis provided on how countries might then make optimal decisions on 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.

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[14] Production of land-based renewable energy would qualify as forestation under the CDM and the cap is 1% of the base year emissions times five for each Annex I Party (Source: para. 14 of UNFCCC 2006: "Report of the conference of the parties serving as the meeting of the parties on its first session, held at Montreal from … Addendum, Part two: Action taken by the conference of the parties", Decision ../CMP.1 on land-use, land-use change and forestry).

Societal 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 organise themselves well in the political process, these will benefit from subsidy-financed programmes. Societal adaptation will be less attractive as benefits are spread more widely.

Nonetheless, at the local level, there is a growing recognition that there are in fact important areas of intersection, particularly when natural and energy and sequestration systems intersect - examples include bioenergy, forestry and agriculture (Morlot and Agrawala, 2004). This is recognized as being particularly relevant for developing countries, particularly Least Developed Countries, which extensively rely 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.*, 2006), on forestry, on agriculture (Dang *et al.*, 2003), and on coastal systems (Ehler *et al.*, 1997).

### *11.10 References*

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