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EXECUTIVE SUMMARY

Introduction

This chapter summarises the sectoral mitigation potentials and costs covered in Chapters 4 to 10 and extends them to allow for interactions between sectors and technologies. It also covers generic technological change and its effects on mitigation and in the modelling of costs and benefits. It provides an assessment of the macroeconomic costs, spillovers and co-benefits of action.

Trends in the carbon intensity of global GDP have changed over the 20th century, with a fall from mid-century as economic growth has become increasingly separated from CO_2 emissions. The reason for the change has been a move in sectoral supply to low-carbon energy, especially natural gas, and a move in sectoral demand to low-carbon services. The questions addressed in the chapter are

- Will this happen anyway?
- If not, what policies are best to manage the problem?
- If these imply unacceptable risks, which policies will be cost-effective to reach agreed stabilization targets e.g. 450 ppmv CO_2 concentrations or 2 degrees warming over the 21 century?
- What is the role of technology in these policies?

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 compilation of mitigation potential across sectors 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, or to block sunlight, remain largely speculative, uncosted and with potential for unknown side-effects. 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.

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 $100/tC. 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.

[to be completed by December 9, 2005 and to be reviewed before January 20, 2006].

The gap with estimates of costs from top-down models has, however, narrowed, partly because some of the top-down models have introduced more bottom-up features, especially experience curves incorporating effects from 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 – though the relative paucity of purely top-down models applied to long-term mitigation limits the scope for meaningful comparison, and the studies emphasise the costs depend heavily upon the technology assumptions.

Technological Research and Deployment

That 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.

Modelling the Effects of Induced Technological Change

A major development since the TAR has been the inclusion in many top-down models of induced technological change. Modelling studies suggest that allowing for induced technological change may lead to substantial reductions in permit prices and GDP costs, compared to those in the TAR in which technological change was assumed to be independent of mitigation policies and action. However, this finding is conditional upon first the assumption of a cost-effectiveness criterion, e.g. the achievement of a given stabilisation target such as 450ppmv, 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 even greater, perhaps by an order of magnitude. Co-benefits of the actions in the form of reduced damages, e.g. less air pollution, would further reduce costs.

However the studies are often very abstract with little technological detail and a very stylised specification of spillover effects. Their empirical basis is very weak; they are highly deterministic and usually fail to account for the major uncertainties. Finally their treatment of policy instruments is very limited. They usually cover only one instrument but when there are two market failures involved (climate change damages and spillover benefits from investment), so that at 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. And if mitigation policy leads to reductions in output, and R&D spending is determined by changes in output, then it also will be reduced. For example, it may be difficult to know when to cut back or promote various elements of the portfolio and, because in the short term the supply of scientists and engineers is finite such approaches may raise wages without generating commensurate more research leads, although in the longer term this will encourage more education and training. 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.

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 fair or democratic, is likely to be inefficient and costly.

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. Modeling efforts have addressed post-Kyoto strategies, and more intricate domestic policies. The second trend has been an evolution of models and modeling, 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 modeling technique, and improved understanding - meta analysis - of existing results.

The Energy Modeling Forum study (EMF19) reveals small GDP costs and a wide range of estimated carbon tax rates hinging on assumptions about baseline emission growth, as well as technology developments with regard to carbon capture, nuclear, renewables, and end-use efficiency. However, the carbon tax rates are all below about $50US/tC to 2030 and 6 of the 9 below $100US/tC by 2050. Three conclusions are drawn. First, technological development, however and under whatever policy it unfolds, is critical in 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, renewables, advanced nuclear, and hydrogen require a long transition as learning by doing accumulates and markets expand so that 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. Although these conclusions are not unlike those in the TAR, they are now more robust after five additional years of model development.

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 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 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). There are many more "framework" or "background" policies, which may yield substantial GHG reductions as ancillary benefits (see Bashmakov, 2003 and 2004 section 11.7 below). All the policies have direct sectoral effects, but also indirect cross-sectoral effects, and these 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 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 and sometimes turned into net benefits through a portfolio of policy instruments including those that help to overcome barriers), with emissions trading in particular expected to reduce the costs. Model projections indicate that long-term growth paths of GDP are not significantly affected by mitigation actions towards stabilisation. However mitigation costs may be significant for particular sectors and countries over some periods and the costs of stabilisation tend to rise as levels of atmospheric stabilisation 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 concern: (1) theoretical and empirical implications of introducing induced technological change on costs in the modelling, implying that higher real carbon prices will accelerate the adoption of low-carbon technologies, lower the costs and even turn them into benefits; (2) further reconciliation between top-down and bottom-up estimates of potentials, and, significantly, more detailed identification of barriers and estimates of their effects on costs; and (3) 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 options not covered in earlier chapters, such as ocean fertilization, cloud creation and bio- and geo-engineering. Section 11.3 considers how technological change contributes to mitigation. Section 11.4 covers overall mitigation potential by sector, bringing together the various options and presenting the assessment of the sectoral implications of mitigation. Section 11.5 brings together the macroeconomic costs. 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; 11.7 covers spillovers from action in one group of countries on the rest; 11.8 covers co-benefits and costs; and 11.9 synergies and trade-offs between mitigation and adaptation.

11.2 Cross-Sectoral Mitigation Options: Description, Characterization and Costs

This section syntheses the mitigation options from Chapters 4 to 10 of Part 2 of the Report, extends the assessment to geo-engineering and other options not covered in Part 2, and concludes by reviewing developments in the top-down, bottom-up literature, which links the modelling and results in Chapter 3 with those in chapters 4 to 11.

11.2.1 Policy options and technology options

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 11.2.1 summarises a large set of policies and measures and what impact they have on the various sectors in terms of results from chapters 4-10 on costs per tonne C avoided and uncertainties of mitigation by main technology and sector.

[INSERT **Table 11.2.1**. Similar to TAR WG3 T3.36, to be compiled from Ch 4 -10, to be completed by December 9, 2005 and to be reviewed before January 20, 2006]

11.2.1.2 A Range of Cross-Sectoral Options

In bringing these options together, it is helpful to organize them into groups, each of which will contribute a sizeable amount to the global reduction on GHGs over the next 50 years. Box 11.2.1 presents a set of options or "wedges" for long-term mitigation drawn from Pacala and Socolow (2004), each of which will deliver a saving of 1 GtC-equivalent over the next 50 years. Current anthropogenic GHG emissions are approximately 6-7GtC-e. These options are judged to be technically feasible. However, they are not explicit in their assumptions about what is included in the base case and whether some of the technology in a particular wedge might already have been assumed to play a role in base case emissions. And they do not consider the economic and social interactions that might result from the steps that they propose.

[INSERT **Box 11.2.1** here]

11.2.1.3 Linkage with Chapters 4-10

Irrespective whether specific technological mitigation options have been designed for specific sectors, or have instead a more generic character, their impact will have a number of aspects in common, such as: does the technology typically affect supply behaviour, or does it rather focus on demand; is the technological knowledge publicly available or patented, and how accessible is the technology for less-advanced market players; does the technology have a bias in favour of large producers or any other bias in favour of specific user groups; what is known about the mitigation potential related to technology investment costs; is the technology linked to specific other technology, capital investment or application, or can it be implemented stand-alone; what can be said about the learning aspects of the technology; etc. In the following the various technological options listed in chapters 4-10 will be assessed from a number of perspectives as listed above.

In addition each technology can be positioned in the technology cycle, as outlined below. Essentially this cycle distinguishes between a number of stages: the fundamental research stage; the pilot stage with small-scale application in a laboratory setting; the stage of the first market pilots (on a non-commercial basis); the first commercial application stage (without the need to make profits from it); the first commercial application stage; the large-scale implementation stage; and the mature implementation stage. Each stage has its own criteria and policy aspects. Table 11.2.2 illustrates where the various technologies can be positioned, and possibly how and how fast technologies have shifted through the cycle, and with the help of what policy action.

[INSERT **Table 11.2.2** here. To be compiled from chapters 4 to 10, to be completed by December 9, 2005 and to be reviewed before January 20, 2006]

11.2.2 Ocean Fertilization and Other Geo-engineering Options

There is a risk that the conventional mitigation options will not be sufficient to achieve atmospheric stabilisation. 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.

11.2.2.1 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 & 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, before going on to explore its environmental consequences and the time scales of carbon sequestration.

11.2.2.2 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. Direct injection of CO_2 into the ocean accelerates a natural process and offers an attractive 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.

11.2.2.3 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 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 metallic screen with 25nm 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 1990,2002) involves seeding low-level marine stratocumulus clouds – which cover about a quarter of the Earth's sur-

face – 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.
[References to WGI and II to be completed.]- Will these be completed by 9th Dec?

11.2.3 Experience Curves across Sectors and Technologies

The definitions and concepts associated with experience curves for technologies are discussed in Chapter 2. This section brings together the sectoral findings. Table 11.2.3, from the survey by Köhler et al (2006) gives some numerical estimates of learning rates from the literature. The great majority of published learning rate estimates relate to electricity generation technologies. The estimates span a very wide range, from about 3% up to over 35% cost reductions associated with a doubling of volumes. Negative estimates have even been reported for technologies when they have been subject to costly regulatory restrictions over time (e.g. nuclear, and coal if FGD costs are not separated). The data do suggest some broad patterns. In many technologies, learning rates appear to be higher in earlier than later stages. Thus early coal development (US 1948-1969) showed rapid learning- in contrast to later evidence (US 1960-1980). Gas turbine data also suggest some evidence of learning depreciation (either kinked or smooth) - learning rates are often more rapid in early stages of development relative to later. Wind energy has demonstrated a wide range of learning rates, with no obvious pattern across locations or even time periods (early versus late development stages). Solar PV in general has enjoyed faster rates of learning than other renewable technologies.

[INSERT **Table 11.2.3** here]

11.2.4 Top-Down and Bottom-Up Sectoral Modelling

The global top-down results in Chapter 3 derive from aggregate global models that reflect either general equilibrium, or endogenous growth, approaches. Most of the sector options and results from Chapters 4-10 as summarised in Table 11.2.1 above and in section 1.4 below correspond to engineering or 'bottom up' methodologies. And results in section 11.5 below are often from hybrid and econometric models. This section assesses the literature on the two approaches and how they are reconciled in hybrid models.

11.2.4.1 Review of TAR and SAR

Assessing the economics of GHG mitigation general relies upon some form of computer modelling, and the IPCC has long recognised that there are many different approaches to this which at the highest level can be grouped into two main categories, usually termed 'top-down' and 'bottom-up'. The IPCC TAR (WGIII, Ch.7, p.489) states that:

> *"Top-down and bottom-up models are the two basic approaches to examine the linkages between economy and specific GHG emitting sectors such as the energy system. Top-down models evaluate the system from aggregate economic variables, whereas bottom-up models consider technological options or project-specific climate change mitigation policies. IPCC SAR on economic and social dimensions (IPCC, 1996a, Chapter 8) includes an extensive discussion on the differences between top-down and bottom-up models. It concluded that the differences between their results are rooted in a complex interplay among the differences in purpose, model structure, and input assumptions"*

> *"In previous studies, bottom-up models tended to generate relatively low mitigation costs (negative in some cases, (i.e. Economic benefits)), whereas top-down models suggested the opposite.*
> *"… the terms 'top' and 'bottom' are shorthand for aggregate and disaggregated models .. '"*

This underlines that the distinction between the two broad categories is important, long-standing and deep-rooted. The TAR offered an extensive analysis of the relationship between technological, socioeconomic, economic and market potential, with some discussion of the various barriers that help to explain the differences between the different levels. The SAR essentially presented results from the two schools of modelling separately, with no significant attempt to bridge the divide. The TAR tended to draw more heavily upon top-down models in the context of assessing short-term costs (such as those associated with the Kyoto first-period targets), but drew more upon results from bottom-up models, or top-down models incorporating bottom-up modelling of the energy sector, in assessing the long run potential for and costs of atmospheric stabilisation. However, it did (necessarily) also draw upon bottom-up models in assessing nearer-term technology potentials, and substantially advanced analysis of the *barriers* that help to explain the difference between shorter term top-down and bottom-up results (TAR WGIII Chapter 6).

The literature since the TAR is probably most notable for advances in three main areas:

- the far wider use of *hybrid* models that seek to combine top-down and bottom-up methodologies at least in some respects;
- some incorporation of barrier analysis into bottom-up modelling, to start generating more behaviourally realistic bottom-up models;
- a richer empirical basis concerning both technological change, and the impact of actual implemented policies that seek to get at the low-cost technological potential identified by bottom-up studies.

This section focuses more upon the modelling developments.

11.2.4.2 Role of Top-Down and Bottom-Up Distinctions in Meta-analyses of Post-TAR Literature on Costs

The adoption of bottom-up or top-down methods makes a significant difference to the results of mitigation studies. In bottom-up studies, specific actions and technologies are modelled at the level of the GHG-emitting equipment, such as vehicle engines, and policy outcomes are added up to find overall results. In top-down studies the behaviour of the economy, the energy system, and their constituent sectors are analysed using data that aggregate to national and regional totals. The methodologies have a fundamentally different treatment of capital equipment and markets. Bottom-up studies tend to suggest that mitigation can yield financial and economic benefits, depending on the adoption of best-available technologies and the development of new technologies. Top-down studies have tended to suggest that mitigation policies have economic costs because markets are assumed to operate efficiently and any policy that impairs this efficiency will be costly. However in the meta-analysis of post-SRES model results (Barker et al, 2002), some models have major bottom-up components, but all have a top-down CGE treatment of the macroeconomy, so it is not possible to identify the effect of the top-down/bottom-up distinction in the analysis.

11.2.4.3 Biases, assumptions, structure of analysis in both approaches; why they give different outcomes

As indicated, bottom-up models tend to yield lower mitigation costs than top-down models. This is generally (though not universally) true for both short and long term mitigation assessments, but the reasons differ quite fundamentally.

(a) Near-term cost estimates.
The main reason for differences in assessment of short term costs arise from the fact that bottom-up technology assessments regularly identify technologies that appear cost effective but are not used, particularly concerning end-use efficiency (the 'efficiency gap'). This contrasts to the market-based assumptions of top-down models. As elaborated in previous IPCC Assessments, bottom-up models:

- focus on measurable technology costs
- generally ignore hidden costs (such as transaction costs, or indirect disadvantages of lower-emitting technologies) that impede take-up of newer technologies
- have a weak representation of the inertia in the systems concerned

These factors mean they tend to *underestimate* near-term mitigation costs *(Energy Modeling Forum, 1996; Jacoby, 1998; Jaccard et al., 2003a, 2003b).*
.
In contrast, top-down models generally:

- measure the aggregrate impact of economic instruments (such as higher prices)
- assume the economy starts from (and is projected at) an optimum state or at least that inefficiencies cannot readily be removed (alternatively, that 'cost free' efficiency improvements should not be attributed to mitigation policy)
- tend to assume that CO_2 mitigation is a discrete action, separate from the diffusion of technologies with multiple benefits
- have no direct representation of the potential for accelerated deployment of improved technologies to reduce both costs and emissions

These factors mean they tend to *overestimate* near-term mitigation costs.

(b) Long term cost estimates
In longer-term assessments, the 'efficiency gap' becomes far less important relative to other assumptions underlying the difference between top-down and bottom-up. Bottom-up models generally project technology-cost reductions arising ultimately from engineering assessments, and thus allow the technological potential for low-carbon innovation to be projected into model results. Top-down models, in contrast, have been largely technologically blind: they have made little use of technology data, but rely on projections of past trends and relationships to estimate the response of

economic systems to changing conditions. This tends to result in higher costs than models that embody explicit technology assumptions (Bohringer, 1998).

The limitations of purely top-down models in the longer term context are such that in fact, many models often classified as 'top-down' actually have bottom-up components particularly for energy supply technologies. This is one class of hybrid models, considered further below.

11.2.4.4 Micro-level Explanations of how Top-down and Bottom-up each relate to Real-world Considerations

The TAR offered an extensive analysis of the relationship between technological, socioeconomic, economic and market potential, with some discussion of the various barriers that help to explain the differences between the different levels. The sectoral chapters (4-10) have each elaborated various barriers to the wider or more rapid adoption of low carbon technologies. This section offers a brief synthesis and classification. The right-hand column indicates the scope for measures to overcome the barrier; in broad terms, the greater the potential to reduce the barrier, the more that mitigation costs might be expected to move towards the assessment of 'bottom-up' models.

Table 11.2.4 sets out some of the barriers to effective mitigation policy derived from Chapters 4 to 10 (to be completed). This barrier analysis is primarily relevant to the shorter term cost considerations. To the extent that barriers can be reduced, this would tend also to reduce mitigation costs in the longer term, but longer-term costs will tend to hinge even more on the progress in low-carbon innovation. By its nature, this is hard to predict. The most empirically-based evidence comes from observations of 'experience curves' discussed above.

[INSERT **Table11.2.4** here – to be completed from Chapters 4 to 10, to be completed by December 9, 2005 and to be reviewed before January 20, 2006]

Where bottom-up models employ experience curve relationship, this has emerged as one of the most important determinants of cost differences between these models and top-down models. Explicit representation of learning can considerably reduce mitigation costs (see sections 11.3 and 11.5; Edmonds *et al.*, 2000, 2004a; Jacobsen, 2001; Löschel, 2002; Berglund and Söderholm, forthcoming). In contrast, top-down models as covered in the TAR generally did not allow for any such learning or scale economy effects, and tended to be particularly weak in their representation of the potential for new technologies to grow in market share and to decline in costs.

11.2.4.5 Modelling efforts to reconcile top-down and bottom-up perspectives

The years since the TAR have seen extensive progress in models seeking to reconcile top-down and bottom-up perspectives. Again, these efforts fall into two main categories.

Behavioural and market diffusion models.
Jaccard *et al.*, (2003a; 2003b; 2004; 2005) include detailed technology representation within a behavioural model of technology uptake and barriers, concluding that this could roughly treble the costs of meeting steep near-term emission reduction targets as compared to more naïve pure technology bottom-up models. Koopmans and Willem te Velde (2001) also seek to integrate energy bottom-up information on efficiency technologies with a top-down demand model. These models tend to confirm that the mitigation costs arising fall between those of top-down and bottom-up models.

Long-term hybrid models

Many authors have now sought to included some bottom-up elements in otherwise long-term 'top down' models (Dellink et al; McFarland *et al.*, Schäfer and Jacoby; Frei et al; and many models participating in an EMF study published in a journal Special Issue (Weyant *et al.*, 2004). In general, the results again confirm that the costs arising tend to fall between those of purely top-down and bottom-up models – though the relative paucity of purely top-down models applied to long-term mitigation limits the scope for meaningful comparison, and the studies emphasise the costs depend heavily upon the technology assumptions.

11.3 Technology Research, Development, Deployment, Diffusion and Transfer

This section considers cross-sectoral issues related to the development and deployment of new technology. It covers the processes of technological research, the way technologies are developed, deployed and transferred over regions and across industrial sectors. A central issue for the costs of climate stabilisation is how technological change relates to economic development, and whether policies to induce low-GHG processes and products will lead to faster or slower development. In other words, can portfolios of climate policies accelerate development? The section considers the long-run processes of CO_2 emissions, economic growth and technological change in the global market economy, the emergence of new sectors, and how technology and change are represented in models of climate change mitigation, and public policy to promote technological change for such mitigation. The estimates of market costs and benefits are covered in Sections 11.4 to 11.6 below.

Greenhouse gas emissions depend fundamentally on the technologies used by firms and end-use consumers to produce and use products, especially those from the supply and use of energy. Many technologies are specific to sectors, and these have been covered in Part 2 of the Report above; but many cut across the sectors, and they interact so that transformation of whole systems of technologies, in particular energy supply and transportation, is involved for widespread and effective mitigation. In large energy-intensive industrial settings, e.g. cement production or oil refineries, multiple interactive technologies are deployed in costly, long-lived, complex systems. Many component technologies are embodied in capital equipment with a productive lifetime measured in decades. The transport sector is similar and it interacts with the energy sector because it uses oil and may in future use electricity on a large scale. Advances in technology offer an important opportunity to reduce future emissions both from existing and new facilities. Improvements can occur through the more widespread utilization of existing energy-efficient technologies, through their more efficient operation and, over longer times, through the invention and global deployment of new technology. In considering options to mitigate emissions it is important to understand these complex processes in a market setting.

Discussions of technology usually identify various phases of activity that contribute to innovations, demonstration projects, commercial deployment and widespread use. Different people and social groups are involved ranging from academic scientists and engineers, to industrial research labs, consultants, firms, regulators, suppliers and customers. In the creation and dissemination of revolutionary, currently non-existent technologies the path to development may proceed sequentially through the various phases, but for existing technology, interactions can occur between all phases, e.g. studies of limitations in currently deployed technologies may spark innovation in fundamental academic research. The ability to identify and exploit advances in unrelated fields (advanced diagnostics and probes, computer monitoring and modelling, control systems, materials and fabrication) is one of the prime drivers of innovation and improvement. Such advances draw from an enabling environment that supports education, research and industrial capacity.

In the process of innovation the behaviour of competing firms plays a key role. Especially in the effort to develop and introduce new non-commercial technology into a sustainable commercial operations, firms require not only the ability to innovate and to finance costly hardware, but also the managerial and technical skills to operate them and successfully market the products, especially in the early stages of deployment and diffusion. The development of proprietary intellectual property and managerial know how are key ingredients in establishing competitive advantage with new technology, but they can be costly and difficult to sustain. The cost and pace of any market response to climate change concerns will depend critically on the state of existing technology, anticipated rates of growth in energy demand and turnover of existing capital stock, and the cost, performance and availability of technologies with lower emissions in the future. The state of technology and technology change can differ significantly from country to country and sector to sector depending on the starting point of infrastructure and technical capacity and the readiness of markets to provide commercial opportunities.

11.3.1 Technological Change, CO_2 emissions and Economic Development

The economic growth literature is too extensive to review here, but it is clear from the study of historical growth over past centuries that technological change is closely associated with growth. Looking back over the last 200 years, the global economic system has been transformed by industrialization, a process that appears to be at its most dynamic in the current generation. Figure 11.3.1, derived from data in (Maddison, 2001), shows how world GDP began growing as the industrial revolution based on coal, iron and water transport developed in the 18th century. As technologies diffused and the extent of the markets widened through trade, the world economy began a period of sustained but uneven long-term growth, which accelerated (see Figure 11.3.2) in the mid- and then the late 20th century. The system is being transformed at a rate unprecedented in the historical record, led and enabled by the exploitation of technology, migration of labour from traditional to modern sectors in developing countries, and international trade. The global economy seems to be characterized by ongoing fundamental change, rather than convergence to any steady state. Long-run growth and structural change through socio-technical systems are described by Freeman and Louçã (2001).

Maddison (2001) finds growth rates to be very different across groups of countries and over time, and ascribes the comparatively high rates of growth to technological progress and diffusion. He argues that the increase in growth rates that emerged in Europe since 1500, and that became endemic from 1820, were founded on innovations in banking and accounting, transport and military equipment, scientific thinking and engineering. He also finds that inequalities between nations in per capita GDP have increased (in particular since WW2), not diminished over time. Technological progress associated with investment is intimately related to Denison's (1967, 1985) causal factors[1]

[1] Denison's study of US growth 1929-1982 attributes the average long-run rate of about 3%pa to six factors: about 25% to labour at constant quality, about 16% to improvements in labour quality as from education, 12% to capital, 11% to improved allocation of resources, e.g. labour moving from traditional agriculture to urban manufacturing, 11% to economies of scale and 34% to growth of knowledge.

(capital, economies of scale and knowledge) accounting for 57% of growth. More recently, Wolff (1994a, 1994b) has found strong correlations between investment embodying technological change and growth in OECD economies.

[INSERT **Figures 11.3.1 to 11.3.4** here]

Tooze (2006) has linked Maddison's GDP data with WRI (2005) CO_2 emissions data as shown in Figures 11.3.3 to 11.3.4. The burning of fossil fuels in all their forms - coal, oil, gas - has been since the 17th century a major technological driver and facilitator of economic growth in industry, transport and agriculture (through the use of artificial fertilizers). The combustion generates both local pollution and increasing concentrations of CO_2 in the global atmosphere. Figure 11.3.3 shows how the trends in the carbon intensity of GDP have changed dramatically in the 20th century, as economic growth is increasingly separated from CO_2 emissions through the switch in supply to low-carbon energy, especially natural gas, and the switch in demand to low-carbon services. The two notable breaks in the series are associated with the rising in oil prices in the 1970s and the collapse of the Soviet Union in 1989-90. In the long-term context, the question is whether this falling trend will continue through the next century. Figure 11.3.4 shows CO_2 emissions in relation to global GDP. Sustainable development implies that the slowing of the rate of growth in the curve will turn into a major decline as the global economy is decarbonised. The questions are:

- Will this happen anyway?
- If not, what policies are best to manage the problem?
- If these imply unacceptable risks, which policies will be equitable and cost-effective to reach agreed stabilization targets e.g. 450ppmv CO_2 concentrations or 2 degrees warming over the 21 century?
- What is the role of technology in these policies?

11.3.2 Outlooks and Base Case Assumptions

Efforts to assess the potential of various technology or policy options to reduce future GHG emissions depend sensitively on base-case projections of future emissions and underlying technologies (Edmonds, 1999; Edmonds *et al.* 2000). Both the absolute level and sources of emissions projected by the models depend strongly on assumptions regarding the treatment and rate of technological progress. The literature has developed substantially since the TAR in exploring how technology may interact with the economy (endogenous technological change in the modelling). However, projected outcomes remain highly uncertain, and different assumptions can lead to significantly different long-term outcomes, e.g. the maturation of a hydrogen economy or its absence. A consistent analytical approach is required to determine whether proposed options to limit emissions may have already been assumed to be present in the base case, and the degree to which their utilization impacts other elements of a scenario or forecast.

Consistent analytical frameworks are also required to assess reliably how various technological options might interact with one another once deployed on a scale significant enough to affect global or even regional energy demand. For example, options, such as hydrogen fuels, that may rely on natural gas as an input could affect overall supply, demand, and prices of all fossil fuels and thereby non-linearly affect the economic viability and the extent of deployment of all future technologies. Similarly, innovations that may occur in areas having little or nothing to do directly with mitigating greenhouse gas emissions, e.g. in advanced seismic imaging and oil drilling technologies or on automotive engine efficiencies may significantly alter assumptions regarding oil depletion that may have a profound affect on base case emissions, economics and potential timing of transitions to alternate fuels.

The scale of investments required to meet growing energy demand and to replace existing capital stock are significant. The International Energy Agency (IEA WEIO 2003) estimated that, without substantial carbon taxes or emission trading schemes, meeting future energy supply needs through 2030 would require a cumulative global investment of $16 trillion in the base case. Note that this total does not include investments for end use equipment, but only for power generation and distribution and for the extraction of fossil fuels (oil, gas and coal). Of this total about $10 trillion would be for the electric power sector with $4.5 trillion for generating capacity and $5.3 trillion for transmission and distribution. Investment in new and replacement oil production would require $3.1 trillion and a similar amount for natural gas production and distribution. As the IEA noted technology could dramatically alter their long-term investment outlook. For example, if carbon sequestration technologies were deployed in power plants investment costs would rise significantly, with knock on effects for site selection and for fuel use and resource depletion.

Scenarios of future greenhouse gas emissions, such as those of the IPCC or IEA, make many assumptions regarding the types of technologies to be deployed in coming years. While most base case scenarios and outlooks do not directly consider the possible implications of climate change policy, they do assume that the ongoing policy environment will at least continue to result in economic growth and a steady pace of ongoing efficiency improvements (autonomous energy efficiency growth when technological change is exogenous in the models).

11.3.3 The Challenge for Research, Development and Deployment of Technology

Two recent studies put forward distinctly different views regarding the readiness of existing technology to mitigate climate risks. Hoffert et al (2002) call for a major increase in research funding to develop innovative technological options because, they argue, existing technologies will not achieve the required deep emissions cuts. On the other hand, Pacala and Socolow (2004) argue that known current technologies could be deployed over the next 50 years to stabilize CO_2 concentrations at 500 ± 50 parts per million - a level that they cite as solving the climate problem. These distinctly different conclusions are likely to arise in part over different viewpoints regarding the costs of deploying mitigation technologies now and in the future and also the costs that society may be willing to bear to limit greenhouse gas emissions. Both analyses are necessarily stylised and simplified. Both provide few estimates of costs for the investments considered and no opportunity costs for the use of funds. Furthermore they give no indication of the relative magnitude of learning-by-doing in the new technologies, a key feature in them becoming economic as their markets expand.

Analyses of implications for costs and interactions between competing technologies are widely available from integrated assessment studies that seek to identify which technologies would become part of a future economy under various assumptions about the cost, performance and availability of a portfolio of technical options. That 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. Developments in the debate about the timing of policy are considered in Section 11.6 below. In the end, the description and treatment of future performance and costs for existing and putative technologies remains a fundamental challenge in the analysis of long-term costs of climate mitigation. Developments in the literature in modelling technologies are considered next.

11.3.4 Modelling technology development and diffusion: the effects of induced technological change (ITC)

A major development since the TAR has been the inclusion in many models of induced technological change, replacing the previous assumption that technological change is autonomous and unaffected by climate policies. Table 11.3.1 lists the implications for modelling of autonomous 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.

[INSERT **Table 11.3.1** here]

The role of assumptions in the models and their results is crucial. Meta-analyses of studies of the costs of mitigation (Reppeto and Austin, 1997; Barker *et al.*, 2002; Fischer and Morgenstern 2003) have concluded that the costs are largely explained by what is included in “costs” and by the assumptions made in characterising the problem. Moreover Barker at al., considering the post-SRES results, were able to explain the GDP costs equally well by a quadratic equation explaining GDP change by CO_2 abatement estimated simply on the basis of knowing which modelling team had provided the estimates. These results suggest that differences between the teams were as important as differences in the assumptions they made in the relationship between the CO_2 abatement and the change in GDP. Many of the models used in the sectoral literature are computable general equilibrium (CGE) models calibrated on one year’s data. McKitrick (1998) found by experimental solution on such a model that differences in form of the production function led to radically different results. Hence to understand the findings in the literature on the effects of technological change, it is necessary to look in detail at the assumptions adopted and at the precise specification of key equations.

There have been substantial additions to the mitigation literature since the TAR in the modelling of endogenous and induced technological change across all sectors of the economy, with an edited book (Grübler et al, 2002) and four special issues of journals addressing the topic (Resource and Energy Economics, vol. 25, 2003; Energy Economics, 2004, vol. 26; Ecological Economics, 2005, vol.54; and Energy Journal, 2006). These issues include reviews, adding to the general literature (Clarke and Weyant, 2002; Grubb *et al.* 2002; Löschel, 2002; Jaffe, *et al.* 2003; Goulder 2004; Weyant, 2004; Smulders, 2005; Vollebergh and Kemfert, 2005; Edenhofer et.al., 2006; Köhler *et al.*, 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 technological change is introduced.

This section reviews the effect of including technological change in the models, induced by policy i.e. ITC, on their estimates of the costs of mitigation, particularly in the near-term costs to 2050. There is a critical divide in the findings in literature depending on the criteria used for the policy implications. Some studies integrate mitigation with climate change and adaptation with assumptions about maximising welfare in cost-benefit analysis (e.g. Nordhaus, 2002); others adopt a cost-effectiveness criterion, examining policies to achieve a given reduction in emissions. As shown in section 11.5 above, these give very different results for costs. The cost-benefit studies tend to be highly aggregated and are perforce very long term, and are covered in Chapter 3; the cost-effectiveness studies tend to be sectoral and more medium term, e.g. addressing the costs of Kyoto, and it is these that are largely reviewed here.

The review shows how the high costs of mitigation associated with the top-down global models, which are evident in many of the results reported in the TAR, are partly due to their treatment of technological change as exogenous. The costs are reduced when R&D responses, technological substitution and learning-by-doing are included in the models and induced by policy, making technological change endogenous. The modelling studies generally introduce these different methodological improvements separately, yet in theory they may well act together and re-enforce and increase the reduction in costs. Several studies report net benefits in terms of marketed output from stringent mitigation targets, adding to benefits from revenue recycling (see 11.5 below) and environmental co-benefits identified in the TAR and discussed in 11.8 below. This development towards hybrid top-down/bottom-up models is also bringing about a convergence in cost estimates towards the low costs of mitigation evident in the technology-rich bottom-up results reported in Chapters 4 to 10 above.

11.3.4.1 The Top-Down Modelling of Induced Technological Change (ITC)

Table 11.3.1 shows the economies for technological change in three groups: effects through R&D expenditures, learning-by-doing (LBD) or specialisation and scale. The treatment within the models is presented in Tables 11.3.2 from Sijm (2004) and Table 11.3.3 from (Edenhofer *et al.*, 2006).

[INSERT **Tables 11.3.2 to 11.3.4** around here]

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) stress the importance of considering the net effect of climate policies, but they differ on the issue of the extent of "crowding out" or substitution between one form of R&D and another. For example an increase in R&D to support the continued use of carbon-based fuels, as in coal gasification and carbon capture and sequestration, may be offset in its effects by a reduction in coal-extraction R&D induced by the carbon-price increase. The first 3 studies assume complete substitution; but Buonanno et al (2003) do not divide R&D and so assume no crowding out, while Popp (2004) suggests that the empirical evidence favours something in between. Thus, the outcomes in the models depend on the approach taken, and the precise specification of the equations involved and their parameter values.

Sijm (2004) provides a comprehensive assessment of the top-down modelling of induced technological change (ITC) and this is summarised below. The models covered by the survey are listed in Table 11.3.2. As noted in many of the other reviews, there is a wide divergence between models in the way they have introduced ITC, the assumptions they have adopted and their results. Mostly, the effect in reducing mitigation costs is large and positive, but some studies find it to be small and even negative. The most important reasons for differences in costs are

1) the policy criterion adopted: cost-effectiveness studies report much larger reductions in costs from ITC
2) the channel adopted for ITC: the use of learning-by-doing variables in the models yields much higher estimated effects of ITC
3) the assumption of "crowding out" of R&D expenditures: if new R&D is assumed to be in addition to existing R&D this has much larger effects than if it is assumed to lead to a reduction i.e.

no net increase, because all R&D resources are assumed to be fully employed. (See below.) A key to understanding the effect of R&D in the models is the relation of knowledge stock to other factors of production, if it is a substitute or complement
4) differences in a few critical parameters, such as the learning rate, the elasticity of energy or carbon R&D investment with respect to energy/carbon prices, and substitution rates between energy sources or energy and capital: higher learning rates, and higher responses of R&D to relative prices lead to greater reductions in estimated costs of mitigation
5) the treatment of spillovers: this varies widely, with many studies not including spillovers; when they are included they magnify the effects of the originating ITC
6) other features in the modelling: the scope and level of aggregation, the number and types of policy instrument and the time horizon: more detail, more instruments and longer time horizons all tend to lead to higher ITC effects.

Sijm (2004) evaluates the strengths and weaknesses of the studies. They are usually based on micro- and macro-economic theory, covering both supply and demand balances and feedbacks. However the studies are often very abstract with little technological detail and
a very stylised specification of spillover effects. Their empirical basis is very weak, they are highly deterministic and usually fail to account for the major uncertainties, and as stated above, they usually analyse only one channel for ITC when there are multiple channels. Finally their treatment of policy instruments is very limited. They usually cover only one instrument but when there are two market failures involved, so that at least two instruments should be included for policy optimisation (Jaffe *et al.* 2004). The important lessons from the literature seem to be 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. And if mitigation policy leads to reductions in output, and R&D spending is determined by changes in output, then it will be reduced. To prevent such effects, Sijm argues, mitigation policies should be accompanied by other technology and education policies to improve the supply of low-emissions R&D resources. In addition, the environmental co-benefits of the technologies should be taken into account.

Table 11.3.1 from Edenhofer *et al.* (2006) in the International Modelling Comparison Project (IMCP) lists the treatment relating to technological change in many models covering a wide range of approaches. One objective of the project is to provide robust results on the modelling of ITC. They find that ITC reduces costs of stabilization, but in a wide range, as found by Sijm (2004), depending on the flexibility of the investment decisions and the range of mitigation options in the models. All models indicate that real carbon prices for stabilisation targets rise with time in the early years, 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. They draw a lesson of the design of a safety valve that might cap emission permit prices: if the cap is too low, the price signal may be insufficient to induce long-term technological transformation. Another robust result is that ITC reduces costs when models include low-carbon energy sources, such as renewables and nuclear and carbon capture and sequestration, as well as energy efficiency and energy savings. Finally policy uncertainty is seen as an issue. Long-term and credible abatement targets and policies will reduce some of the uncertainties around the investment decisions and are crucial to the transformation of the energy system.

Edenhofer at al (2006) conclude that the results for effects of ITC depend on
1) baseline effects: assumptions about the role of technology can lead to relatively low costs of mitigation

2) the assumption of full employment of resources: if the economy is already at an optimum, mitigation policies must be costly; any policy-induced change, such as more low-carbon R&D or more investment in low-carbon energy, must be at the expense of other R&D or other investment.
3) how the investment decision is modeled: typical CGE assumptions having much smaller implications than assumptions used in growth and energy-system models.
4) the modeling of the backstop technology: 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.

They also assess the relation between model type and estimated costs of mitigation. They find that CGE models tend to calculate higher costs that energy-system or growth models, but the reason is not necessarily the model type, but the assumptions each group of modelers tend to make e.g. about foresight. Energy-system models include energy costs; but they usually omit macroeconomic feedback and hence macroeconomic costs and benefits. They omit most rebound effects and any crowding out of investment. CGE models often reduce the flexibility of investment substantially compared to growth-model treatments.

11.3.4.2 Modelling Policies that Induce Technological Change

Chapter 2 and the discussion above emphasise that technological change is a feature of market economies and occurs without policy intervention. Over the past decade there has been a much greater interest in how mitigation policies might accelerate such change in the direction of low-carbon technologies. Goulder (2004) divides the policies into two groups: direct emissions policies, such as carbon taxes and trading (cap and trade), raising the price of carbon-based energy and so raising the profitability of new low-carbon processes and products (market-pull); and technology-push policies, such as subsidies to R&D in low-carbon technologies (subsidy-push), or performance standards. (The policies and measures are considered in Chapter 13 below.) Both types of policies can affect technological change through the three channels described in Table 11.3.2 above:
1) raising R&D in research institutes, firms producing all types of fuel (as they diversify or seek to capture new markets) and firms using carbon-based fuels
2) learning-by-doing through increased experience in using new technologies leading to reductions in costs of low-carbon investment, e.g. in wind power
3) further economies of specialisation and scale leading to new products and industries.

However subsidy-push R&D will not necessarily lead to adoption of the technology by the market and hence learning by doing, while market-pull R&D will normally be driven by, and associated with, investment and learning-by-doing. It is worth noting that these policies (subsidies to research and those raising real carbon prices) work simultaneously through both channels of increasing the stock of knowledge, in as much as they increase R&D spending, and of learning by doing. Thus models should include channels if they are to pick up the full effects of induced technological change on costs of mitigation. Many models include one effect or the other and few include both. It seems likely that the effects through each channel would reinforce each other so that the combined effect will be grater that the two separate effects.

Market-pull R&D effects associated with increases in energy prices have been studied by Popp (2002) for US patent activities in 11 energy technologies 1970-1998. “The price elasticities found suggest the reaction of the research community to a change in policy, such as a carbon tax, will be swift, and that higher prices would quickly lead to a shift toward environmentally friendly innovation. In addition, the positive knowledge stock coefficients suggest that the usefulness of the existing base of knowledge is important to inventors — inventors "stand on the shoulders" of their predecessors." (p. 176). Popp also finds that "The regression results suggest that government-sponsored energy R&D does little to affect private energy patents." (2002, p. 177). This suggests that subsidy-push energy R&D in this form may have a weak, or even counter-productive, effect on private-sector innovation measured by patent activity. The purpose of the R&D is however more long-term i.e. "blue sky" research, but the results suggest that simply encouraging low-carbon R&D, without any way of turning this into innovation is unlikely to be effective.

11.3.5 R&D, Commercialization (public, private) drivers, barriers and opportunities

Public interest is served when innovative products, processes and services become available that provide enhanced performance and/or lower costs to consumers, or that result in safer, less polluting outcomes. Markets create incentives for successful commercial innovation. The policy challenge, in the context of mitigating greenhouse gas emissions, is to create the incentives, or disincentives, that promote successful innovation to reduce greenhouse gas emissions that may not be commercial in current markets. Jaffe *et al.* (2004) indicate that environmental and research policy measures may be needed to overcome excessive GHG emissions and the market failures arising because the innovators cannot retain sufficient value from their R&D to make it profitable. They note that such policies are likely be more effective if harnessed to tap into market-oriented behaviour. However, they also make clear that little can be said about the ultimate cost and effectiveness of efforts to develop revolutionary technology with such a long-term horizon as is represented by the climate change issue.

Commercial innovation occurs predominantly in firms with the know-how to harness technical invention in the marketplace by capturing benefits of advanced manufacturing processes or by providing advanced goods and services. However, the intellectual basis for technical inventions has many sources including fundamental science-based research often from academia, harvesting of seemingly unrelated advances in other areas of commerce and society, evolution of markets, public needs and aspirations, publicly funded research in support of national initiatives, for instance in space, medicine and the military, national laboratories, and proprietary research in firms aimed directly at commercial innovation. A number of innovations can be enabled by cross cutting technologies such as sensors, probes, control systems, materials fabrication, catalysis, etc. that typically need to be optimized for particular applications. Public support for innovation must aim to promote invention across this diverse array of institutions and players, and must recognize that it is typically impossible to succeed by directing funding targeted to a specific objective or technology. For this reason many studies cite the need for a portfolio approach, especially in research support to develop fundamental innovations.

In many markets innovation is a strategy pursued by some firms to achieve competitive advantage. This can occur, for example, by providing products that succeed in the marketplace through enhanced performance or by lowering production costs to deliver similar products at lower price, for example in commodity markets. However, because research and development is costly, unsuccessful efforts or innovations though successful that cannot be used to recoup their R&D costs can harm the competitiveness of companies that seek to innovate. Consequently, some other firms choose rather to be fast followers than to be innovators. Their efforts aim to emulate innovation quickly while being more adroit at capturing ultimate financial benefits in the marketplace. In any event, most firms in competitive markets must innovate at some level to keep up with more successful competitors who are introducing attractive goods and services at lower costs. Again the challenge for policy is to harness and reward successful innovation.

Firms deploy advanced technology through investment projects. While new technology may be deployed in stand-alone, grassroots applications, more often it will be introduced into existing operations through projects designed to upgrade, retrofit or debottleneck existing systems. Thus technologies are introduced as part of an evolutionary process of continuous upgrades in large industrial complexes as well as though independent stand-alone introductions. Use of new technologies often requires appropriate enabling conditions such as trained personnel, regulatory frameworks, and commercial standards.

Where investments are made by companies that own, operate and sell products, technology transfer and capacity building occur automatically as part of the strategic development of a company's business plan. Global companies that rely on innovation and the development of proprietary intellectual property as part of their effort to succeed competitively, typically seek to identify and spread successful innovations as part of ongoing management objectives. The situation can be quite different in public investment projects where authorities seek for example to create a new power station and must rely on various contractors to acquire access to technology and construct new facilities. In this case access to intellectual property may pose legal and financial barriers.

11.3.6 Public Policy to Promote Innovation for Greenhouse Gas Emissions Mitigation

Turning to technology Jaffe et al (2004) note that successful abatement of pollution through advanced technology is a two-step process: innovative technology must not only be invented but also deployed. Firms that invest in innovation create knowledge and hardware that others may benefit from without having incurred costs. Thus the externalities associated with innovation spillovers may decrease the incentive of firms to innovate. While patents and various protections of intellectual property, e.g. proprietary know-how, seek to reward innovators, such protection is inherently imperfect, especially in global markets where such protections are not uniformly enforced by all governments. Similarly, in the early adoption of technology learning by doing (by producers) or learning by using (by consumers) may lower cost to all future users but in a way that does not adequately reward first movers. Finally they note that lack of information by investors and potential consumers of innovative technologies may slow the diffusion of technologies into markets. In fact, they highlight the "huge uncertainties surrounding the future impacts of climate change, the magnitude of the policy response, and thus the likely returns to R&D investment" exacerbate these technological spillover problems.

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 because governments have a poor track record when picking technical winners or losers. Unfortunately, such an approach may generate apparently unwelcome overheads. For example, it may be difficult to know when to cut back or promote various elements of the portfolio and, because in the short term the supply of scientists and engineers is finite such approaches may raise wages without generating commensurate more research leads, although in the longer term this will encourage more education and training. 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. The allocation of funds becomes a political rather than a market decision. 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.

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

11.4.1 Issues to be Addressed

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, 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 demand, 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 plantation may cause massive land-use change, thus affecting GHG emissions from forestry and agriculture.

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.

11.4.2 Integrated Summary of Sectoral Chapters (chapters 4-10):

11.4.2.1 Approaches to Aggregate Sectoral mitigation Potentials

Correct aggregation of the potential for emissions reductions by sectors requires separate aggregation of emission levels, baselines, and reductions per se. Each task is not trivial. While sectoral emission inventory methodology is well established, the aggregation of emission baselines even in one sector is a challenging task and aggregation of sectoral potentials even more so (see IPCC TAR, chapter 3). In the sparse literature on techniques to integrate sectoral emissions, baselines and mitigation potentials, three very important aspects are noticeable:

1. How are energy and non-energy related mitigation potentials to be aggregated without missing part of the potential or double counting it? E.g. double counting when some GHG mitigation

potentials from agriculture, waste management (incineration) and forestry are related to energy use

2. How is energy consumption in end-use sectors to be translated into primary energy and how then is emission mitigation potential to be presented? Such transformation may be done just for electricity, or for both electricity and district heat, or for all activities in the energy sector. Following this sequence the role of the energy sector in emission balance and mitigation potentials changes. Another aspect is technique for the end-use energy to primary energy transformation: whether it is done on the assumptions of historical energy sector technologies and fuel mixes or whether it is to account for evolution of past or foreseeable technological and energy resources.
3. How will technological progress, price signals or behavioral changes in one sector impact on activity levels and market situation in others? It is clear that emissions are a function of both activity levels and emission intensities of those activities. Activity levels in each sector depend, among other drivers, on the speed of new technology penetration and behavior changes, induced among other factors by price evolution, some of which comes from other sectors. High oil prices lead to switching to more energy-efficient equipment; energy-efficiency improvements in end-use sectors as a feedback lead to lower activities in the energy sector; introduction of new building materials may affect the index of industrial production; and intensive dematerialization of industrial sector and development of effective communication systems leads to less cargo and lower passenger transport activities, etc.

The IEA statistics on CO_2 emissions by sectors are based on energy (primary energy minus all energy transformation, transport, and distribution losses) delivered to end-users for six sectors: public electricity and heat production, unallocated power and heat auto-producers, other energy industries, manufacturing industries and construction, transport (with separating road transport), other sectors (with separating residential sector). When such approach is used, energy transformation sector is represented by three subsectors and accounts for 45% of all global CO_2 emissions in 2002 with transport ranked second at 24% (IEA, 2004). Presented in this way energy sector is responsible for about 60% of global CO_2 emission growth 1971-2002. This approach highlights the energy-sector role in mitigation policies and actions. This role is demonstrated by the fact that all present registries and emission trading systems are densely populated by energy companies, which are playing the leading role in mitigation actions (IETA, 2004). Traded ER units are mainly generated by projects with renewable energy technologies, cogeneration, flare vent reductions, and fuel switch in power and heat generation sectors. Emission-reduction potential by sectors may be aggregated using the same IEA methodology.

The TAR (Chapter 3, table 3.1) approach, also adopted in AR4, to sectoral emission allocation is based on end-use sectors with the energy sector either not shown explicitly (US EPA, 1999 and Price, 2005) or left to what is called in IEA statistics “other energy industries”, which include energy consumption and losses in fuels mining and extraction, refining, transport and distribution. Such an approach may be more or less comprehensive. When LBNL constructed time series for evaluating sectoral trends in global energy use and greenhouse gas emissions, primary to secondary (not end-use) energy factors were calculated for electricity, heat, coal products and petroleum products (Price, 2005). So both gas transmission and distribution losses and secondary energy used in energy sector (for example electricity and petroleum products needed at coal transformation facilities) were not accounted for. This approach misses the fact that for “other energy industries” sector to produce and deliver a unit of energy to end user, not just primary energy resources is needed, but secondary energy carriers are used as well. With this approach the energy sector moves from centre stage, since its emissions are allocated to other sectors. Sectoral policies and measures then concentrate exclusively on end-use sectors.

Such an approach may use constant final energy to GHG emissions coefficients for each sector, assuming a country-or region-wide stable fuel mix and energy-transformation efficiency. The weakness of such approach is that it ignores technological progress and resource-base evolution in the energy sector. Such end-use to primary energy coefficients may instead be assumed to be dynamic. It is easy to evaluate dynamic coefficients for the past. The approach in chapters 4 to 10 is to make them dynamic in the future on the basis of recalculating results of SRES scenarios A1 and B1 (Price, 2005). In this case the contribution of the energy sectors to mitigation is completely allocated to the end-use sectors. Often only power generation efficiency and GHG emission factors are considered, so other energy-sector activities are left as separate sector to be included with other industries. Table 3.1 in the TAR does not show the energy sector in the historic 1990 emissions (all its emissions are included in other sectors) and presents the mitigation potential (Table 3.37) in the energy sector for 2010 and 2020 including fuel switch and improved power and heat generation efficiencies, leaving energy sector role in overall potential to 2.6 to 5.8% of the total (IPCC, 2001).

Bashmakov (1993) uses another approach to aggregate sectoral potentials based on the following presentation of relationship between the primary and final energy consumption by sectors: $PE= AE*PE+FE$, or $PE=(I-AE)^{-1}*FE$, where PE is a vector of primary energy consumption by energy carriers, AE is a square matrix of full coefficients of primary energy carrier i to produce and deliver to end-user one unit of energy carrier j, FE a vector of final energy consumption by energy carriers and I is the unit matrix. It shows sectoral sums for energy carriers. Each a_{ij} coefficient in AE shows how much primary energy (biomass, coal, petroleum products, gas, primary and secondary electricity, and heat) are needed to main, extract, enrich, refine, and deliver to end-users one unit of, say, coal. While this approach requires additional data collection, it provides for more correct and significant primary to final energy coefficients. Any change in consumption of each final energy carrier, even if it is not electricity or heat, brings measurable direct and indirect changes of primary energy-resources consumption and then in emissions. Any change in energy-sector technologies leads to a change in the AE matrix to AE^*, and this also produces direct and indirect emission reduction effects. Without accounting for such technological change within energy sector, the indirect effects generated by changes in sectoral activities would be overestimated. Based on this methodology the emission-reduction potential for Russia in early 1990s was divided into direct and indirect effects induced by changes in final energy use and by changes in technology and fuel mix in energy sector totals. The potential for reduction from the 1990 level was 42% for energy-related emissions with the contribution of the energy sector at 36% (Bashmakov, 1993).

All potentials are related to baseline activity levels. In turn all activities are influenced by technology. Input–output analysis clearly explains that energy consumption in each sector is a function of all technological coefficients and all activity levels through the whole economy either directly or indirectly. So the task of integration means finding effective and comprehensive integration tools. This is not just a matter of adding together the potentials identified in Chapters 4 to 10. One weakness of the bottom-up approach adopted in these chapters is the absence of intersectoral analysis with a lack of accounting of the effects of a given technology penetration on activity levels in other sectors. The simple sum of potentials may be larger then integration of potentials accounting for mutual influences between technologies in one sector and activities in other sectors. Such effects are treated in top-down models, but these tend to extrapolate past technological and behavioral inertia into the future.

11.4.2.2 Aggregated GHG Emissions Mitigation Potentials

This section collects and consolidates results of aggregation of GHG emissions mitigation potentials presented in chapters 4-10 above. The set of corresponding definitions of potentials and costs are given in chapter 2. Market potential refers to GHG abatement as a result of actions inspired by market forces, that is, in the absence of any governmental intervention. It depends in large degree on the price level and decision-making patterns. It is efficient in that it shows the outcome of private decisions under existing prices, budget limitations and business discount rates. However the decision-maker possesses limited information on the costs and benefits from potential actions. To go from the information to decision-making and actions, the market agent identifies its own budget limitations or a lending institution evaluates its creditworthiness. The more the budget limitation or the higher the risk perception, the higher are the business discounts rates. This means that there is large uncertainty in evaluation of the country-wide or global market potentials. Income distribution and development of financial institutions are as important factors as prices, which are also different in different countries and even for country regions and consumer groups. That brings additional uncertainty, when sectoral potentials are aggregated. Growing oil prices have escalated market potential in recent years. So the base year for calculating estimates of market potentials becomes a real issue, when sectoral numbers are to be compared and integrated.

Among many other things, while integrating sectoral potentials, the consideration of "price-response potential-activity" relationships becomes very important for GHG emission reduction evaluation. When the energy-cost share in gross output or personal income reaches or goes beyond a threshold it negatively impacts on activity levels and so the potential economic growth is not realized, affecting GHG emissions. This effect may be well illustrated by the residential energy use or personal transportation sector. In all countries the ratio of households' energy consumption expenditures (fuels, electricity, and district heat) to family income stays in the narrow range of 2 to 5%, as does the costs of transport equipment operation and public transportation services 5% to 7%. (Eurostat, 2001). Both these proportions are fairly stable in time: in the US in 1959-2004 they varied in the ranges of 1.8% to 3.2% and 5.0% to 6.6% of the corresponding personal income (Council of Economic Advisers, 2004). When energy prices climb steeply and ratios of energy costs to incomes reach thresholds, consumers have a limited short-term possibility to respond by improving efficiency and part of their reaction becomes one of reducing consumption or (if it is possible) by refusing to pay (Bashmakov, 1988 and Bashmakov 2004). "Bashmakov's wing" presents a demand function with changing energy consumption to energy costs/income elasticity. Elasticity substantially grows when energy costs to income ratio reaches or goes beyond thresholds and while the purchasing power limit reaches -1. So, suppliers do not benefit any longer from price growth. Consumers become mobilized, but short-term options are limited. In such situation significant price growth faces limited purchasing power and leads to reduction of energy consumption or low payment discipline (Eurostat, 2001, UNDP-GEF, 2005, Bashamakov, 2004). Lack of energy brakes activities in many sectors and GDP growth. This negative effect is mitigated by policies to enhance market potential.

Enhanced market potential is based on the system of enhanced decision-making and actions-taking created by specific polices to motivate market agent to realize larger scope of available options. *Economic potential* shows what is efficient to implement when decisions are to be taken by all market agents (not by the government itself) but at social discount rates and including the cost of carbon or GHG permits or taxes. If all decisions are made by a government the scope of the potential shrinks substantially due to inability of the central government to collect and processes all information, which is required for efficient decision-making. If responsibility to make decisions is not delegated and managers are reluctant to take on responsibilities, then decisions are taken predominantly on the basis "one size fits all" and such decisions are far from being efficient. So the potentials different depending on the decision-making frameworks (see chapter 12). *Technical potential* presents the amount by which it is possible to reduce greenhouse gas emissions or improve energy efficiency by implementing a technology or practice that has already been demonstrated. There is no specific reference to costs here, only to 'practical constraints' although in some cases implicit economic considerations are taken into account. Technical potentials were reported by chapters 4-10, when economic information was lacking. Pacala and Socolow (2004) estimated that technical potential of scaling up seven from twelve considered already known technology wedges is sufficient to "shave" the emissions growth and to fill the stabilization triangle. Each of presented 12 wedges capable to mitigate 3.7 $GtCO_2$/yr. To stabilize the emission or to shave the emission growth originated form energy use until 2030 reduction of 10-28 $GtCO_2$/yr is needed (see XXcross referenceXX). So technically speaking 22-63% of 12 twelve wedges potential is needed to stop emission growth prior 2030.

When chapters 4-10 are evaluating potentials the following factors were taken into consideration to make results more homogeneous and comparable: discount rates, year of cost estimate, costs nature (private/social, project/technology/sector), cost items, reference baseline. Another issue for getting homogeneous results is using common matrixes and units: monetary units, emission units.

The major results of the potentials integration (aggregation) are presented in Tables 11.4.1 and 11.4.2 below. Table 11.4.1 generalizes potentials presented in sectoral chapters and allows seeing the scale of potential on the background of past emissions as well as A1 and B1 SRES scenarios. For the year 2020 the potential evaluated in TAR is presented. This table conceals the role of separate technologies or wedges in the potential evaluation. To disclose it the Table 11.4.2 presents results of greenhouse gas emission reductions studies not only by sector, but also by technology, region, costs and some other assumptions.

[INSERT **Tables 11.4.1 and 11.4.2** here, similar to TAR WG3 T3.37 to be compiled from CH.4-10, to be completed by December 9, 2005 and to be reviewed before January 20, 2006.]

11.4.3 Studies on Energy Supply-demand Interactions

11.4.3.1 The Carbon Content of Electricity

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 11.4.1 illustrates the interactions of CO_2 mitigation measures in electricity supply- and demand- sectors.

[INSERT **Figure 11.4.1** here]

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% while the CO_2 emissions from power supply sector are reduced by 7.6%. 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 system (CGS, combined heat and power supply) in residential and commercial sectors considering the indirect effects on the CO_2 emissions from power generation sector using a long-term optimal generation-mix model. In a standard scenario where coal-fired power has economic advantage to meet the incremental electricity demands, the installation of CGS achieves the reduction of CO_2 emission in the total system because CGS replaces mainly coal-fired power plants with high CO_2 intensity. However, in a different scenario, the CO_2 reduction effect of CGS introduction may be substantially lower; for example, the effect is negligible when very highly efficient CCGT (combined cycle gas turbine) plants are replaced by CGS plants. And, in the case where nuclear power is replaced by CGS, the total CO_2 emission from energy system conversely increases with CGS installation. These results suggest that the CO_2 reduction potential by the introduction of CGS should be cautiously evaluated taking into consideration the future power plant construction program

11.4.3.2 The Effects of High Energy Prices on Mitigation

There is a literature on asymmetrical price responses and effects of technological change (Gately and Huntington, 2002). Price responses of energy demand can be much larger when energy prices are rising than when they are falling, whereas conventional modeling has symmetric responses. Thus the mitigation response to policy may be much larger when energy prices are rising than when they are falling. Bashmakov (2006) also argues for asymmetrical responses, an analysis of what author calls the economics of constants and variables - the existence of very stable macroeconomic proportions, which may be observed for the all period of statistical observations (over 200 years): ratios of labour costs, profits, material costs and energy costs to gross output. He argues that there is threshold for energy costs as a ratio of gross output of 5-6%. If energy prices are escalating and push this ratio to exceed the given threshold, then it provokes a negative relationship between the energy cost-share and GDP growth. This changes the dynamics of energy-demand price responses. The closer the ratio to the threshold, the larger is the absolute value of the price elasticity. So high energy prices bring a change in regime to lower economic growth. 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/gross-output ratio to the threshold.

Low oil prices cannot be sustained for a long period. Demand for energy escalates due to low energy prices and the lower price elasticities. So when spillovers occur they are temporary. The theoretical postulate on of high production-factor substitution may be incorrect in the CGE calculations of leakage and competitiveness. In reality, the induced technological change leads to the substitution of low-quality production factors by the same production factors with higher quality. This finding has many implications for technology diffusion, spillovers effects and sustainable development.

11.4.4 Studies on Interactions of Mitigation Options involving GHGs from Land-use Change

There are interactions in the use of biomass in the energy sector with the waste management and land-use sectors. Possible interactions are illustrated in Figure 11.4.2

[INSERT **Figure 11.4.2** here]

As shown in the figure, there are positive and negative interactions in terms of GHGs emissions. In case of the interactions between energy and waste management sectors, there are positive interactions in the sense that possible CH4 and N2O emissions are reduced by the energy applications of waste biomass. Interactions between energy and land-use sectors, however, could be negative when a large-scale bioenergy plantation is considered. If a large area of forest is converted to energy plantation, there is a risk to decrease substantially the carbon stock in forest and soil even when the plantation is operated in a sustainable manner (see 11.9 below).

Yamamoto *et al.* (2000) evaluate CO_2 emissions reductions taking into account the integrated effects of land-use changes and the energy system with a global land use and energy model (GLUE), which describes competition for land use among agriculture, forestry, and energy plantation on the basis of overall biomass flows as well as energy systems. There are two important results. 1) Large scale introduction of modern fuelwood by felling and planting in existing forest will cause drastic reduction of the mature forest area. Thus, the CO_2 emission reduction caused by the fuel substitution from fossil fuels to the fuelwood will be mostly cancelled by the additional CO_2 emissions caused by the land-use conversion from the mature forest to the growing forest which contains less carbon stock. 2) When energy recovery from paper scrap is given priority over material recycling, bioenergy will substitute partly for fossil fuels while the decrease in recycled paper scrap will cause an increase in demand for new paper from growing forests. Thus, the net reduction of CO_2 emission becomes as small as that in the case of a large-scale fuelwood plantation.

11.4.5 Cross-Sectoral Effects of Greenhouse Gas Mitigation Policies

The cross-sectoral effects of mitigation policies can be assessed by different criteria, amongst which are mitigation costs and mitigation potential. Findings have shown that policies designed to mitigate climate change in one or more sectors of the economy may invariably give rise to cross-sectoral effects, which can be positive or negative. Unfortunately however, the issue of attributing costs to cross-sectoral effects of greenhouse gas mitigation policies has not been studied 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 all 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/tCO2, 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 11.4.3 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 N2O 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.

[INSERT **Table 11.4.3** here]

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 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 GLODYM, 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. However the model assumes that wage rates are fixed in nominal terms, so that the social security reductions have a limited effect on the labour markets. The effects on GDP and labour are summarized in Table 11.4.4. The table shows that a uniform tax rate of up to 10US$/t CO_2 in 2010 induces varying effects in the G7 countries – for example, GDP losses range from -1.72% for the US to -0.23% in Japan. The authors go further to investigate the effects of carbon taxes on industrial output. The results in Table 11.4.5 indicate that decline in petroleum and coal products will be strongest, while on the other hand, the effects on construction will be mild.

[INSERT **Tables 11.4.4 and 11.4.5** here]

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 11.4.6 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. Figure 11.4.3 shows the average GDP loss relative to the baseline for both the tax and tax plus subsidy regimes, showing the substantial reduction in costs if the subsidy option is taken.

[INSERT **Table 11.4.6** and **Figure 11.4.3** here]

11.4.6 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 11.4.7). The table also shows the gains through international trading both across the EU and in Annex I, confirming the benefits reported in the TAR.

[INSERT **Table 11.4.7** here]

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/t-CO2e for the sector target and $120/t-CO2e for the national target while those of industrial sector are $300/tCO2e and $120/tCO2e respectively. Correspondingly the GHG abatement cost for the electricity sector is $(1995)15.71 bn for the sector target and $(1995)28.47 bn while those of industrial sector are 34.41 and 11.25 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 inefficient and costly.

11.5 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. While the SAR sought to reconcile the significant differences between bottom-up and top-down models, the TAR focused on the importance of international regime, domestic policy design—particularly revenue recycling, ancillary benefits, and modeling technological change. 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. Here we see both modeling efforts addressing post-Kyoto strategies, on the one hand, and more intricate domestic policies on the other. The second trend has been an evolution of models and modeling, 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 modeling technique, and improved understanding—meta analysis—of existing results.

11.5.1 Models in Use and Measures of Economic Costs

[INSERT **Table 11.5.1** here]

Table11.5.1 lists the models discussed in this chapter that have been used to estimate macroeconomic 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, as well as proposals in the U.S. and Japan for, and implementation in New Zealand of, carbon taxes.

11.5.2 Technology Assumptions and their Effects on Aggregate Costs

A key area of model development has been representation of the process of technological change in models, as described in section 11.3.4 above. This section discusses the effect of the new treatments on emission permit prices, carbon tax rates, GDP and/or economic welfare. 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 active investments (suggesting a delay in mitigation until costs decline) or by passive accumulation of experience (suggesting an acceleration in mitigation to gain that experience, and lower costs, earlier). This issue is discussed in Chapter 3 and section 11.6 below. Overall, the TAR noted that differences in these technology assumptions were a central determinate of differences in estimated mitigation costs and other impacts.

Since the TAR, there was been considerable focus on the role of technology modeling in estimating the impact of mitigation policies, though syntheses of this work tends to reveal more uncertainty than clarity (Weyant 2004). Modeling efforts have explored a range of approaches to modeling technological change, focusing on (1) explicit investment in research and development (R&D) that increases the stock of knowledge, (2) the costless accumulation of applying that knowledge through ”learning-by-doing” (LBD), taken here to include all the different components of increasing returns discussed in 11.3.4; and (3) simple sensitivity analyses to cost assumptions.

11.5.2.1 Aggregate Costs in Models with Endogenous Technological Change (ETC)

In his ETC 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, he finds considerable variation in the effect of including ETC. While most models find a large reduction in mitigation costs (Sue Wing, 2000), some find small or even negative impacts (Nordhaus, 2002). He attributes these differences to (a) whether carbon-saving R&D crowds out other investment; (b) assumed rates of return to R&D; (c) rates of learning (if LBD is included); and (d) degree of spillovers across sectors and regions. Popp (2004) similarly finds assumptions about crowding out and the rate of return to R&D to be critical to the estimated impact of endogenizing technological change. The reasons for the differences are discussed next.

Nordhaus (2002) uses his R&DICE spreadsheet model to compare (separately) the effects of (1) ITC via R&D (2) Kyoto with Annex I trade and (3) including a US climate-friendly technology programme (the 2000 programme of tax credits $3.6bn and R&D investments of $1.4bn continuing in real terms indefinitely). He finds that for the US the effects of the technology programme are small and high-cost, about 15% of the Kyoto effect 2010-20, but rising to become comparable by the end of the century. At the global level the effects of the programme are negligible compared with those from introducing ITC, but these in turn are very small compared with other studies, suggesting that the “climate change problem is unlikely to be solved by induced innovation” (p. 205). However Goulder and Matthai (2000) are able to place these results on ITC effects in a more general context, encompassing the Nordhaus estimates. Their model covers both R&D as new knowledge and learning-by-doing LBD (although they report them as separate effects, not in combination) with an analytical solution and a wider sensitivity analysis. Their results show that the Nordhaus findings of negligible effects come about as a result of the adoption of the cost-benefit criterion and the R&D channel. They find that with the 550ppmv target there are potentially large effects of introducing ITC, with a central reduction of 29% in the tax rate with R&D by 2050 and 39% with LBD. Table 11.5.2 shows the effects on the abatement, tax and benefit levels and paths for two policy criteria (cost-effectiveness, as in the 550ppmv stabilization target, and cost-benefit, optimizing discounted global monetized welfare) and for ITC channels, mainly R&D and LBD. The table compares numerical solutions in central values and ranges from sensitivity tests (all as % differences from the no-ITC cases). Since these effects may well combine and re-enforce each other, the overall reduction may be over 90% in the central case.

[INSERT **Table 11.5.2** here]

In contrast to the results for top-down models, Sijm (2004) finds considerably more consistency among bottom-up models, where the effects of learning 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 11.5.3.

[INSERT **Table 11.5.3** here]

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 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.

In simulations comparing the fixed/endogenous technology path for various climate targets, the endogenous path always lowers costs. But in some cases the cost reductions are quite large (a factor of six) while in others they are small (a few percent), analogous to—but even more varied than—the top-down results reported in Sijm (2004). The two panels (a) and (b) in Figure11.5.1 below show the costs of the 3 stabilisation scenarios in terms of gross world product (GWP) in 1995 prices, discounted at 5%pa without and with ITC. As before, the variation depends on whether R&D investment crowds out or supplements other investment and the implied return to climate-induced investments. The models with the largest effects in the IMCP study, MIND, FEEM-RICE, ENTICE and E3MG, are all models where the long-run dynamics of aggregate growth itself are endogenous. Those with the very largest effects, MIND and FEEM-RICE, have backstop technologies with learning-by-doing whose costs fall more rapidly when the technology path is endogenous (Edenhofer *et al.* 2005).

[INSERT **Figure 11.5.1** here]

It is notable that FEEM-RICE and E3MG with technological change suggests that climate stabilization policies lead to higher GDP, although in FEEM-RICE the increase is lower the more stringent the target and in E3MG growth is higher with more stringent targets. In FEEM-RICE, the outcome is dominated by whether there is international cooperation or not. It is assumed that there are spillover benefits (externalities) from R&D that cannot be captured by firms, hence R&D investment is below optimum in the baseline. The reason that climate policies lead to higher GWP is that they require international co-operation, and this leads to R&D subsidies, higher R&D and economic growth.

The reason for higher growth in E3MG is quite different. E3MG represents a new methodological approach to long-run mitigation policies, since it is a non-optimizing, econometric model in which economic growth is demand-led and supply-constrained, whereas the other models discussed above all optimize supply-led growth in a general equilibrium framework. In E3MG, it is assumed that resources are not fully employed in all world regions, so that co-operative climate policies can lead to higher investment in low-carbon processes, increasing returns to specialization and scale, and a faster movement of labour from traditional to modern sectors, especially in developing countries. With higher emission permit prices, even faster technological change is induced and economic growth is slightly increased. The effect is further elaborated in (Barker *et al.*, 2006). With no ITC, they find that to achieve stabilization at 450ppmv CO_2 by 2100 requires a permit price of $US(2000)17/tC in 2011 escalating to $680 by 2050 for the energy sector, with a corresponding carbon tax in the rest of the global economy. With ITC these rates fall to $10 and $400 respectively. The global growth rate in this scenario is 2.9%pa 2000-2050 with no ITC and 3.1%pa with ITC. In the baseline with ITC, but with CO_2 concentrations rising to unsustainable levels, GDP growth is slightly lower at 3.0%pa.

11.5.2.2 Other studies of technology and aggregate costs

Instead of focusing on various models of ETC and the effects of turning it "on" or "off", one can more generally examine results from various models and ask how assumptions about technology development, endogenous or exogenous, affect estimates of aggregate costs. Weyant (2004) summarizes the results of Energy Modeling Forum (EMF) 19, a study constructed along these lines. The summary results reveal very small GDP costs (Weyant, 2004, 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 11.5.2 shows how the rates are very low, all 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 $150US/tC in August 2005.

[INSERT **Figure 11.5.2** here]

Perhaps more revealing in EMF 19 is the chosen focus by various modeling teams in their respective papers contributing to the study. Edmonds et al (2004) focus on carbon capture and disposal technology, hydrogen production, and fuel cells. They consider the impact of a roughly 30% decrease in carbon disposal and hydrogen production costs by 2100, as well as significant declines in the cost of capturing CO_2 from large fossil plants. These assumptions more than halve the tax-rate costs of a achieving a particular target. Riahi *et al.* (2004) look at carbon capture technology only and consider the effect of an endogenous reduction in costs from learning by doing, versus the exogenous reduction in Edmonds et al (2004). Despite some dramatic tax-rate cost declines - by a factor of four by 2050 in A2 550ppmv stabilisation - the effect on GDP losses is almost negligible, with the losses almost unchanged at about 1% of GDP by 2050 and from 2 to 3% GDP by 2100 for B2 and A2 550ppmv stabilization. The reason is partly the responses of the WorldScan CGE but also perhaps because, unlike Edmonds et al (2004) they do not consider a simultaneous improvement in hydrogen production and fuel cell costs. Mori and Saito (2004) focus on a linked decline in the cost of producing hydrogen from fast breeder reactors. Compared to a scenario with no expansion of nuclear capacity, they find annual GDP costs roughly halve from 0.4 to 0.2% by 2050 and from about 1.3% to less than 0.6 % by the end of the century. The shadow prices of carbon are also much lower until about 2080.

Van Vuuren et al (2004) consider the effect of a halving in cost of electricity generation from renewable (solar/wind) sources; they find that such technological progress doubles the volume of reductions achievable by a given carbon price over several decades. Manne and Richels (2004) consider the impact of an unspecified carbon-free energy source, finding that a substantial reduction in the cost of this energy source could lower the cost of a particular target by forty to seventy percent. Akimoto et al (2004) present a slightly different analysis, decomposing the total volume of reductions over the next century by source of reductions. The largest single source (39%) is from end-use energy savings. Smekens-Ramirez Morales (2004) and Kurosawa (2004) both focus on a variety of sequestration technologies, and (interestingly) both find relatively little variation in overall mitigation costs, given a 550 ppm target, for alternative assumptions about sequestration costs. McFarland et al (2004) and Sands (2004) also focus on capture and sequestration, the former finding a 25% decline in the cost of stabilization by 2100 and the latter finding a roughly 30% decline in the cost of a 600 MtC reduction in 2030, both versus a case without capture and sequestration technology. Hanson and Laitner (2004) focus on energy-efficiency technologies and, based on assumptions of significant returns to investment in these technologies, find reductions of 40% by 2050 with a net economic gain.

Summarizing, six teams focused on carbon capture and sequestration, one on nuclear, one on renewables, two on end-use efficiency, and one on an unspecified carbon-free technology (one team focused on impacts rather than technology). 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. While there is the potential to consider these results a sign of hopeless ignorance, they do in fact 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, renewables, advanced nuclear, and hydrogen require a long transition as learning by doing accumulates and markets expand so that 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. Although these conclusions are not unlike those in the TAR, they are now more robust after five additional years of model development.

11.5.3 Policy Analysis Since the TAR

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 modeling as the Kyoto Protocol has come into force. At the same time, specific policies in the European Union (the EU Emission Trading Scheme) and proposals in the United States (S. 139 and S. 2038 in the 108th Congress, the Regional Greenhouse Gas Initiative, the Pavley Bill in California, and the proposal by the National Commission on Energy Policy) have led to more detailed studies covering specific sectors and regions, as well as coupling emission and technology policies. Finally, growing interest in efforts beyond the Kyoto compliance period and targets has generated additional studies examining long-run stabilization scenarios.

11.5.3.1 Kyoto Studies

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 (McKibbin and Wilcoxen 2003), the withdrawal of the United States (Manne and Richels 2001), banking and the use of “hot air” (den Elzen and de Moor 2002; Manne and Richels 2001), and CDM accessibility (den Elzen and de Moor 2002). Figure 11.5.3 provides one estimate of the impact of different assumptions about the answers to these questions on the equilibrium permit price.

[INSERT **Figure 11.5.3** here]

As indicated in the figure as well as other studies, the aggregate cost of meeting the Kyoto target, without the United States, without any banking of hot air, and with favorable baseline outcomes, could be negligible. On the other hand, banking of excess allowances by countries facing a surplus, higher growth rates, all associated with higher permit prices, could substantially raise aggregate costs.

11.5.3.2 Domestic Policy Studies

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.

11.5.3.3 Policy Studies in 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 summer 2005 debates over comprehensive energy legislation. Costs and other consequences of those proposals are summarized in Table 11.5.4, as compiled by Morgenstern (2005) from studies by the U.S. Energy Information Administration (1998; 2004; 2005)

[INSERT **Table 11.5.4** here]

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. 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. The real GDP losses shown for Kyoto (+9%) are reduced to 0.3% by 2020 when non-CO_2 GHG and recycling benefits are taken into account.

As an independent, government statistical agency, EIA's modeling results tend to lie at the center of most policy debates in the United States. 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.

In addition to the aforementioned studies focusing on recent policy proposals, additional work on costs in the United States has focused on distribution. Rose and Oladosu (2002) and Dinan (2004) both document regressive impacts of climate change policy, noting that grandfathering allowances is more regressive than recycling 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.

Policy Studies in Canada

Jaccard et al (2003a and b) provide estimates of costs of reaching the Kyoto targets in Canada as part of their larger effort to reconcile top-down and bottom-up modeling results. Using their benchmark run, and assuming compliance without international trading, they find an allowance price of C$150 per ton CO_2e 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.

Policy Studies in Europe

Since TAR, several studies have been analysing the macroeconomic costs in Europe of committing to Kyoto or other targets, different trade regimes, and multiple greenhouse gases.

Babiker et al (2003) use the EPPA-EU model to study the idea that emission permits trade may be welfare decreasing in some cases. With non-optimal taxation in the pre-trade case, a rise in energy prices on top of an already distorted fuel price constitutes an additional welfare loss that might outweigh the gains from sales of permits. 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.

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 11.5.5. 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.

[INSERT **Table 11.5.5** here]

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, 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 €/tCO_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 €/tCO_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 €/tCO_2 to less than 5 €/tCO_2, and the annual compliance costs are reduced by another 60%.

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. 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%,.

Policy Studies in Japan and Asia

A number of studies have been published since the TAR covering policies in Japan, China, and India. Masui et al (2005) estimate that a 45,000 Japanese yen (JPY) 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 3,400 JPY/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. If growth is closer to 2%pa, it will be nearly impossible.

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 11.5.4 below). Table 11.5.6 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.

[INSERT **Figure 11.5.4** and **Table 11.5.6** on China here]

11.5.3.4 Post-Kyoto Studies

Bollen et al (2004), using Worldscan a global CGE model, consider the consequences of post-Kyoto policies seeking a 30% reduction for Annex B countries below 1990 levels by 2020. They do not include the CDM, sinks or induced technological change in the modelling. Like most studies, they find dramatically lower costs when global trading occurs. With only Annex I 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/tCO2 and there is a much lower loss of 0.6% in GDP.

11.5.4 Difference Across Models

Research has continued to focus on differences in various cost estimates across models (Weyant 2000, 2001; Fischer and Morgenstern 2003; Weyant 2003; Lasky 2003; Barker and Ekins, 2004). 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 (2003) 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 (2003) 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 (US EIA, 1998). 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 11.7 below.

11.6 From Medium-term to Long-term Mitigation Costs and Potentials

The IPCC TAR laid out various debates around the timing of mitigation actions in the context of long-term goals. Analysis since then has increased the empirical basis upon which to estimate some of these influences, and the balances between them for the potential policies, sectors and technologies to which they could apply. The focus in this section is upon these "transition and timing" issues, particularly concerning the relationship between the horizons covered in Chapters 4-10 (focused mostly on the first quarter of the Century) to the longer term global analyses in Chapter 3 concerning how trends might lead towards stabilisation in the second half of this Century. The associated "aggregating" literature on the relationship between near-term actions and long-term outcomes, that bears upon both the timing and the portfolio of different responses, falls into three main classes of issues:

- Inertia, capital stock and the timescales of transition processes
- **Innovation processes and interactions between "new" systems**
- Strategic decision-making in the context of uncertainties, irreversibility, and intergenerational impacts

11.6.1 Inertia, capital stock and the timescales of transition processes

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. Lempert and Hart (2002) caution against overly simplistic interpretations of nameplate lifetimes, emphasising that "capital has no fixed cycle". Whilst initial-stated lifetimes may drive maintenance schedules, they are "less significant drivers of plant retirement or investment in new facilities – with regular maintenance, capital stock can often last decades longer than its rated lifetime". On the supply side of energy markets, 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 11.6.1. 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.

[INSERT **Table 11.6.1** here]

Energy systems studies further emphasise the timescales involved. Even oil, despite its huge economic advantages over other fuels, took close to a century before it dominated energy supplies, and it has taken at least 50 years for each major energy source to move from 1% penetration to a major position in global supplies; see Figure 11.6.1. Electricity systems penetrated the US in two major "long waves" of around 50 years each (Ausubel, etc). Moreover, these were processes driven internally by the overwhelming advantages of the new (and generally carbon-intensive) sources of supply. Drawing also on the systems innovation literature (Unruh, 2002) argues 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.'

[INSERT **Figure 11.6.1** here]

Such long timescales – and the even longer periods associated with interactions between systems – have many important implications. In the context of stabilisation, higher inertia brings forward the date at which abatement must begin to start meeting any given stabilisation constraint, and lowers the subsequent emissions trajectory (HaDuong et al, 1997). In the context of stabilisation at 550ppm, van Vuuren et al (2004) find that (excluding learning, discussed below) "inertia results in a 10% reduction of global emissions after 5 years and 35% reduction after 30 years".

From an economic perspective, the implications of inertia of capital stock affect two quite distinct issues: the inertia associated with capital stock already in place; and the inertia associated with capital stock yet to be constructed. These considerations apply to both supply and demand infrastructure.

For *existing stock*, Lempert and Hart (2002) observe that nameplate plant lifetimes "are not significant drivers [of retirement decisions] in the absence of policy or market incentives". The cost of maintaining plant rises as it gets older; decisions are made when major refurbishment or other alterations are required. Practical experience in the UK power sector (Eyre, 2001) highlights this: the considerable retirement of old, inefficient coal plant during the 1990s, which was associated with considerable increase in system efficiency and reduction in emissions, was driven not by technical "age", or by carbon prices, but by sulphur regulations which meant plant owners were faxed with the choice of *either* retrofitting stock or retiring it. With cheap gas plant alternatives and looming carbon risks, many chose the retirement option rather than making major new investment to keep old plant going. Such micro-level 'tipping points' at which investment decisions need to be taken may offer ongoing opportunities for lower risk abatement, since the carbon-intensive choice will involve either committing to emissions for decades to come or risking the higher cost of early retirement in the event that much tougher carbon controls are needed.

New stock construction to meeting rising demand, of course, offers more obvious opportunities than refurbishment to affect the future stock structure. Shrestha *et al.* (2004) illustrate how the CDM could substantially affect the course of power sector developments in three Asian developing 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/tCO2 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 during the second quarter of the Century.

At a global scale, such choices are reflected in the scenarios of the International Energy Agencies' World Energy Outlook (IEA, 2004), which estimate 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. In their "reference" scenario most of the generation investments are in carbon-intensive stock; their "alternative" scenario, with significantly lower emissions, involves more rapid growth in less carbon intensive investments, and although this is more expensive per unit, the scenario actually requires less capital investment overall because of the increased efficiency of end use (even when the end-use investments are included). The IEA emphasise that the choice of path out to 2030 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.

11.6.2 Innovation processes and interactions between "new" systems

The feasibility, pace and cost of a technological transition towards sustainable energy use and production systems will be strongly influenced by the relative cost of higher and lower carbon emitting technologies (the scope for wider use of apparently cost-effective demand-side technologies is such that the main focus of economic and policy research has been upon diffusion, rather than on innovation processes that might lower their cost further). In particular, in many cases the present cost of carbon-intensive supply sources are lower then non-carbon supplies, and if this remains the case then the cost and difficulty of policy measures to drive a transition on to stabilisation trajectories will grow as the scales increase over time. Global modelling and technology studies, as reviewed in various chapters of this report (Chapters 2, 3 and earlier in this chapter) thus emphasise the crucial importance of innovation in reducing mitigation costs, and Chapter 2 in particular contains extensive discussion of innovation processes. This section considers the implication of different perspectives for the timing and nature of policies associated with transitions towards stabilisation trajectories over the next few decades.

As sketched in Chapter 2, and in section 11.4 and 11.6, two broad types of innovation are those of 'R&D-led' and 'market-induced' innovation – often more simply known as "push" and "pull". None dispute the potential role, value and importance of well-managed public R&D, and both the existence of and the qualitative implications of market-induced innovation for environmental policy are also widely accepted: Jaffe *et al.* (2004) note that 'both theory and empirical evidence suggest that the rate and direction of technological advance is influenced by market and regulatory incentive, and can be cost-effectively harnessed through the use of economic-incentive based policy. In the presence of weak or nonexistent environmental polices, investments in the development and diffusion of new environmentally beneficial technologies are very likely to be less than would be socially desirable.'

However quantification of each dimension is complex and their relative influence, as discussed, remains in dispute. Because modelling market-induced innovation is so complex, most global models have tended to use exogenous assumptions about the costs of future technologies. From such models, some studies have drawn the conclusion that optimal policy at present is to focus on R&D rather than abatement (the most famous study being Wigley *et al.*, 1996). In practice such models highlight the importance of technology development but do explicitly represent a view of how to bring it about. The implication could be either to wait, to invest heavily in R&D, or to induce innovation through market mechanisms depending on how the processes are represented.

Anderson and Cavendish (2001) produce the simplest modelling application of the induced-innovation case to climate change. They assume that technology cost is driven by learning-by-doing and that technologies diffuse on the basis of comparative cost according to a standard logistic diffusion curve, and examine how carbon taxes might then affect the 'turning point' of developing country emissions growth. They find that introducing a carbon tax of US$100/tC would lead per capita emissions in developing countries to peak at just over twice current levels after about 40 years and then decline steadily. The carbon tax increases energy prices by about 60% for about fifteen years, after which it declines as the low-carbon technologies mature and start to penetrate energy systems at scale. The later the policy is introduced, the higher the peak emissions and the longer the carbon tax must be maintained to bring emissions down again to comparable levels. Grubb *et al.* (2002) illustrate the potential global importance of induced technical change, if the adoption of Kyoto targets in the leading industrial powers and their subsequent expansion over subsequent rounds, combined with globalisation forces, would help to bring convergence of carbon emissions towards a common average level of emissions per unit GDP.

Such studies help to illustrate the fact 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, as discussed above.

It is important to note, as described above, that models of induced technical change still vary widely and not all give the same properties. Manne and Richels (2004) apply learning-by-doing to backstop technologies in their model and find that 'depending on the sensitivity LBD can substantially reduce the overall costs but with regard to timing, does not significantly alter the conclusions of previous studies.' van Vuuren et al (2004), studying the global emission reductions associated with a carbon tax that rises linearly to US$300 by 2030, find that emission reductions are 40% if the tax were introduced in 2020 and ramped up sharply, but 55% if it was introduced in 2000 and increased more slowly, though in this it is hard to disentangle the effects of induced learning from those of inertia.

In reality of course, innovation arises as a mix of 'push' and 'pull' forces, as discussed in Chapter 2, and this makes drawing policy implications about how action now may relate to technology transitions far more complex. Alic, Mowery and Rubin (2003) analyse US experience with technology policy based upon four general lessons,[2] and derive various specific conclusions for policy divided into three main classes, as summarised in Table 11.6.2. Despite this, they conclude that 'technology policies alone cannot adequate respond to global climate change. The 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.'

[2] 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 (iii) Technology learning is the essential step that paces adoption and diffusion (iv) Technology innovation is a highly uncertain process. [This material may be more suitable for Chapter 2]

[INSERT **Table 11.6.2** here]

Sanden and Azar (2005) delineate the detailed forces underpinning 'carbon lock-in' and 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 independently. 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.

Finally, an IPCC Expert Meeting emphasis and analyses more explicitly the role of industry in technology development, transfer and diffusion, highlighting case studies from many different specific sectors, many of which emphasise the continuous nature of the innovation process from a business perspective, and its intimate relationship to patterns of investment and the incentives for risk-taking over the coming decades.

11.6.3 Strategic decision-making in the context of uncertainties, irreversibilities, and intergenerational impacts

The third major strand of literature relating to "transition analysis" emphasises 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, modeling 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.[3] The early models of Kolstad (1996a and 1996b) appear to make a similar

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

assumption, treating GHG stock (i.e. carbon in the atmosphere) as irreversible but not the GHG-emitting capital that generates it. If this understanding of the models is correct, their relevance to decisions about the appropriate balance between more and less carbon-intensive investments going forward is unclear.[4]

Given the importance of uncertainty and learning – and in particular the modeling result that rapid resolution of uncertainties about the severity of climate damages would (*cetus paribus)* reduce the optimal degree of present abatement - Keller and Kolstad (2001) focus on the other issue of estimating the likely rate of relevant learning. They conclude that it is likely to be slow – many decades – which would tend strengthen the influence of irreversibility effects.

Shue (2005) takes an entirely different and qualitative ethical approach focused on intergenerational 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' (which he notes as 'two facets of one very hard rock').

Finally, only a small literature appears to address how different emission *trajectories* over the next few decades may affect climate impacts. O'Neill and Oppenheimer (2004) examine the implications of three types of pathways towards various target concentrations (500, 600 and 700ppm): *'rapid change'* that follows 'reference' until at least 2030 before departing and stabilising in 2100; *'slow change'* pathways that depart from 2005 and remain on a lower trajectory that finally reaches and stabilises at the target level in 2200; and *'overshoot pathways'* that exceed the target level by 100ppm in 2100 and then decline to the target in 2100. They find that 'the range of temperature outcomes in 2100 across the three types … is about 0.5-1.2 deg.C, as large as or larger than the difference in long-term outcomes for different stabilisation levels.' Moreover, the 'slow change' pathways lead to median rates of temperature change that decline over time from an initial rate of 0.16deg.C/decade (for their central climate sensitivity), contrasting with peak rates of around 0.2deg.C/decade for the 'rapid change' 500ppm case, and approaching 0.3deg.C/decade for the 'rapid change' (and overshoot) scenarios with higher stabilisation levels. The authors conclude that the faster rates of change would both be harder to adapt to, and also would increase the risk of abrupt climate changes such as impacts on the Thermohaline circulation and polar ice melting.

11.6.4 National integrating studies on transitions and timing during first half of this Century

A number of governments and some other regional/state governments have set ambitious long-term CO_2 reduction goals, most of them for mid-Century, typically by 60-80%. Detailed scenarios developed as part of national studies on implementing these goals highlight three major factors in relation to the present implications of such a transition, that corresponding broadly to the three dimensions discussed above:

1. The crucial importance of measures relating to long-lived capital stock. For example in the UK buildings sector, where the slow cycles of both new build and major retrofit highlight that the UK goal of 60% reduction is only achievable if building standards are tightened very rapidly during the present decade, combined with a steady decarbonisation of electricity generation for powering dwelling heat pumps (Johnston et al, 2005).

[4] This interpretation to be checked with authors and against wider literature research in the light of FOD review comments.

2. The need for innovation-related actions on all fronts, both R&D and market-based learning-by-doing stimulated by a variety of instruments ranging from renewable incentive schemes to straightforward emissions taxes or cap-and-trade.
3. The need also for 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.

Terriers and others (2005) combine all three of these perspectives in an analysis of paths to the Dutch target under the combined modelling and stakeholder-based 'COOL' project. Actions are divided into 'Short, medium and long term actions' and they list 33 entries under "short term actions" spanning institutional, fiscal, standards and technology-based measures.. However, no such comprehensive analyses of the relationship between near term and long term actions have been attempted at a global level, and thus attempts to link the more details shorter-term perspectives of Chapter 4-10 with the longer term global stabilisation modelling of Chapter 3 inevitably remains incomplete.

11.7 Spill-over effects

Spillover effects of mitigation in a cross-sectoral perspective are taken to be the effects of mitigation policies and measures in one country or group of countries on sectors in other countries. Intergenerational spillover, which are the effects of actions taken by the present generation on future generations are covered in Chapter 2. In particular spillover effects are the effects of mitigation polices taken by Annex I countries on the rest of the world. They are an important element of the evaluation of environmental policies in economies globally linked through trade, foreign direct investment, technology transfer and information. Whilst much of the literature recognises the existence of spillover, costs and benefits (direct and ancillary benefits), different models produce different conclusions with varying level of uncertainties. Spillover also make the compilation of mitigation potential across sectors more complicated. National or sectoral mitigation potential may be offset or enhanced by spillovers in other regions or sectors, with an added complication that the effects may be displaced over time. The measurement of the effects is made more difficult because they 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. Uncertainty and disagreement over time scale, cost, technology development, modelling approaches, policy and investment pathways lead to uncertainty about spillovers and in consequence mitigation potential.

The same spillover effects 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 modellers (e.g. Babiker, 2005) conclude that Spillover, via carbon leakage, will render mitigation action ineffective or worse if it is confined to Annex I countries. Others taking a broader view (e.g. Grubb et al, 2002) 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 2002, p. 302). 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 of perfect versus "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.

11.7.1 Review of SAR and TAR Treatment of Spillovers

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 energy-intensive exports are gainers, and 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. 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 trading in 2010. The study reporting the highest costs shows reduction of 25% of projected oil revenues with no trading, and 13% of projected oil revenues with Annex B trading in 2010 (WGIII, Technical Summary, 2001, p.60).

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 from world model for OECD action 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. Also, TAR (p 72) noted that future development paths, sustainable or otherwise will shape future vulnerability to climate change, and climate change policies impacts may affect prospects for sustainable development in different parts of the world.

11.7.2 Carbon Leakage

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 CDM projects, e.g. (Gundimeda, 2004), in the case of India (discussed in section 11.7.3 below). Leakage implies carbon and financial impacts within a country, a region and between regions. The carbon leakage pertains to the overall change in emissions. It has been demonstrated that carbon leakage due to a fall in fossil fuel prices 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 (discussed in section 11.6.5 below). 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, (Barreto and Klassen, 2004) due to spillover of learning (discussed in section 11.6.7). Mongelli et al (2006) using an input-output model for Italy assess the scale of relocation according to the pollution-haven hypothesis and also discuss carbon leakage, but are unable to provide any quantitative estimates.

Babiker's (2005) paper presents findings that extend beyond those reported in the SAR and the TAR. The distinctive extension to his 7-region, 7-good and 3-industry global CGE model is the inclusion of a treatment of increasing returns to scale and strategic behaviour in the energy-intensive industry. Assuming the adoption of the Kyoto Protocol by the OECD region, he presents 3 leakage rates, which depend on the assumptions adopted: 25% for increasing returns to scale (IRTS) and homogeneous-goods (HG), 60% for constant returns (CRTS) and Armington differentiated goods, and 130% for the HG-IRTS combination. These are striking results that go beyond the 5-20% rates reported in the TAR. The 130% rate implies that OECD action leads to more global GHG emissions rather than less.

In assessing these finding it is important to understand three critical underlying sets of assumptions

1. The CGE model assumes a global social planner to maximise welfare, full information over space and time, perfect competition, and identical firms in each sector ("representative agents"). The high leakage rates come when the composite energy-intensive good is treated as homogeneous (it includes paper, chemicals and metals). Perfect substitution means that production is assumed to relocate without cost.
2. Increasing returns are included in only one sector. Adopting the assumption for the energy-intensive industry alone is arbitrary since many other products are produced under increasing returns (e.g. electricity-generating machinery, vehicles, computers, software, communications). Indeed the literature (e.g. McDonald and Schrattenholzer, 2001) does not emphasise the technologies used by energy-intensive industries excluding electricity. In consequence, given perfect substitution, all production is likely to relocate, depending on the assumed dynamics in the model, and with increasing returns, the production in the non-Kyoto countries will become more price competitive, hence the 130% leakage rates.
3. Adjustment to a new equilibrium is assumed to take place over 18 years 1992 to 2010. The calibrated base year is 1992 with a solution for Kyoto effects for 2010. In fact Kyoto action has largely taken place after ratification, with the EU emission trading scheme beginning in 2005, leaving a much shorter time for leakage than that assumed. The structure of international trade has also changed substantially since 1992.

The model is showing that the energy-intensive industries will re-locate in response to the change in relative prices brought about by 28% carbon abatement below business as usual by 2010 (the paper does not state which policy is assumed). The result shows the potential for international trade to undermine unilateral environmental policies under special assumptions and conditions. In fact, mitigation action has tended to give preferential treatment to energy-intensive industries, and any trade quotas, e.g. steel quotas, will obstruct relocation.

Sijm *et al.*, (2004) provide an in-depth literature review and assessment of the effects of Annex I mitigation on carbon leakage, especially from a technological perspective, and especially in developing countries. Technological spillovers are considered in section 11.6.6 below. Two aspects of carbon leakage are considered in the review: the effects covered by formal economic models of mitigation policies; and empirical analysis of effects in energy-intensive industries. The modeling results are inconclusive. “Models provide a useful, but abstract tool for climate policy analysis; they are faced by several problems and limitations with regard to practical policy decision- making, including problems such as model pre-selection, parameter specification, statistical testing or empirical validation.” (p. 14). In the empirical analysis of energy-intensive industries, the authors argue that 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. “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, further research is required to reach valid results. “The ambiguous results of the empirical studies in both positive and negative spillovers with the modelling results warrant further research in this field.” (p. 179).

11.7.3 Impact on Sustainable Development

Gundimeda (2004) considers how the CDM might work in India. 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 CPR 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 leakage of carbon benefits 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 an 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 US should pay OPEC and Mexico an estimated compensation of $0.7 billion annually to offsets the adverse impacts on these regions and EUR 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. On the issue of re-location of industry, Sijm *et al.* (2004) conclude that "existing studies cannot provide a clear picture about the effect of environmental policy on the relocation of energy intensive industries; but they do indicate that - if a relation between environmental policy and relocation should exist - it is statistically weak." (p. 165). This section covers price competitiveness, while technological spillover effects are discussed in section 11.7.7 below.

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 (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[5]. (Bernstein et al, 1999).

11.7.5 Effect of mitigation on energy prices

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.). As such, two distinct spillover effects are identified for non-Annex I 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.

11.7.5.1 Effect of mitigation on oil prices and OPEC revenues

As in the TAR, results on the mitigation impact on oil prices are mixed. Some studies point at gains by Annex I 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 (Rutherford, 1999; Pershing, 2000; Barnett, et al, 2004). Jarmo, (2005) in studying the Finland's energy taxation system concluded "It

[5] "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."

is quite clear that differentiated taxation practices make the environmental tax less effective from the perspective of environmental policy". Increases in the level of CO_2 tax on fossil fuels have served mostly fiscal purposes with reduced CO_2 emissions being only a side benefit. This would increase the economic costs of introducing renewable energy resources compared to fossil fuels without taxes. This in turn would distort the energy prices (Wahlund, *et al.*, 2002) [6], and thus make future investments in fossil fuel energy for future supply highly uncertain.

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. They also report results from OPEC's World Energy Model (OWEM) on the effects of Annex B trading on OPEC Member States revenues (see Table 11.7.1 below). 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.

[INSERT **Table 11.7.1** here]

However, OPEC's market power is uncertain. OWEM 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. Nearly all modelling studies that have been reviewed show more pronounced adverse effects on oil-producing countries than on the Annex I countries who are taking the abatement measures.

11.7.6 Compare/explain results from Different Models

Sijm (2004) provides a lengthy discussion on methodologies and how results can be different: "The outcome of the exercise by Grubb *et al.* (2002b), however, depends highly on the (implicit) assumption that mitigation actions in the industrialised countries will induce a large variety of (relatively cheap) abatement technologies that are not only widely adopted in industrialized countries but also in developing countries (even if these latter countries do not have a climate policy incentive to adopt these technologies themselves). Moreover, the study of Grubb *et al.* (2002b) is based on the critical (but unreal) assumption of no emissions trading between Annex I and non-Annex I countries". Bernstein, *et al.* (1999) concluded that "The shift of energy intensive industries out of An-

[6] "When introducing a renewable energy carrier, the cost will increase compared to fossil fuels, as the production costs are higher (excl. taxes and fees)"

nex I countries into non-Annex I countries when non-Annex I countries do not participate in emission trading is significant. Carbon leakage is also significant and is connected with shifts in energy intensive industries, reduced energy efficiency and fuel substitution due to lower fuel prices in developing countries. Investment falls in all regions, less in non-Annex I countries and more in Annex I countries". Nearly all models that have been reviewed show more pronounced adverse effects on fossil fuel producing countries than Annex I countries who are taking abatement measures.

11.7.7 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 spill-over effects. 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.

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 spill-overs 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.

Sijm *et al.* (2004) provide an assessment of 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 11.2 above.) They review the treatment of spillovers in the top-down modeling studies and find that most of them omit the effect or have it playing a minor role. The effects of spillovers combined with learning-by-doing is explored specifically 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 (Sijm, 2004 p.68).

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.*, 2004).

Technologies pertaining to CO_2 reduction in the electricity sectors, on the other hand, may be accessible, but still facing some challenges according to Kumar, et al (2003): "Disseminating energy-efficient technologies, even when they may appear to be technically perfect, is always a tough task, more so in economies with low purchasing power and educational levels". Use of hydrogen-fuel-based energy technology is found to cause such an impact raising yet another problem for the environment as the solution of one problem leads to the creation of another (Alharthi & Alfehaid, 2005). Technology sharing by the fossil-fuel energy suppliers has been severely limited to date. The reason is probably to do with 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 in the electricity sectors, on the other hand, may be more accessible. Modelling of the 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, including portfolio analysis

11.8.1 Introduction

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, 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, both for industrialized and developing countries.

11.8.2 Co-benefits from GHG Mitigation for Air Quality

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 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.*, 2004).

11.8.2.1 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 11.8.1). Mitigation strategies aiming at moderate reductions of carbon emissions in the next 10 to 20 years (typically CO_2 reductions between 10 to 20 percent compared to the business as usual baseline) also reduce SO_2 emissions by 10 to 20 percent, and NO_x and PM emissions by up to five percent. 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; O'Connor, 2005; Aunan *et al.*, 2003 – for China; Bussolo and O'Connor, 2001 - for India; Cifuentes *et al.*, 2001; Dessus *et al.*, 2003; McKinley *et al.*, 2005 – for Latin America). Studies for Europe (vanVuuren, 2005; Bye *et al.*, 2002), North America (Burtraw *et al.*, 2003; Canton, 2000) and Korea (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.

[INSERT **Table 11.8.1** around here]

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-$/t C (Joh *et al.*, 2003; Burtraw *et al.*, 2003) up to several hundreds US-$/t C (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 shown to have largest impacts.

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). 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 percent of estimated mitigation costs (Proost and Regemorter, 2003; Burtraw *et al.*, 2003) up to a factor of three to four (Aunan *et al.*, 2004; McKinley, 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 the potential for CO_2 mitigation in India without net loss in welfare between 13 and 23 percent of the emissions of a business-as usual scenario. For China, this potential has been estimated by O’Connor (2003) for 2010 at 15 percent, and Dessus *et al.* (2003) arrive for Chile at 20 percent compared to the business as usual emissions in 2010. The significant low-cost mitigation potential for some non-CO_2 GHGes in developing countries, e.g., for methane (reference to USEPA study) suggests an even larger scope for no-regret measures if such gases are included in the analysis.

11.8.2.2 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 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 percent 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, O’Connor *et al.* (2005) 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 17.5 percent 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.

11.8.2.3 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.* (2005) 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.

11.8.2.4 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 percent, 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.* (2005) 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 percent 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.

11.8.2.5 Summary of the Air- quality Co-benefits from GHG mitigation

While the above studies use different methodological approaches, there is general consensus for all analyzed world regions that near-term health 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 show.

11.8.3 Synergies and Trade-offs between Air-pollution Control and GHG mitigation

From a portfolio perspective of GHG mitigation, the most important linkages between climate change and air pollution exist at the level of emission sources. 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). 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.

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.

11.8.3.1 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 (Dentener *et al.*, 2004; Fiore *et al.*, 2002).

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.

11.8.3.2 Biofuels

Particularly relevant trade-offs have been identified for GHG mitigation strategies that enhance the use of biofuels and diesel. Bio-fuels, if grown in a sustainable manner, are considered carbon neutral and thus have been suggested as an important element of decarbonisation strategies. However, their combustion releases large amounts of fine particulate matter and volatile organic compounds, which cause significant negative health impacts. Emissions are especially high from combustion in household devices in under uncontrolled conditions, which is typical for developing countries. 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.*, 2000).

11.8.3.3 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).

11.8.4 The Need for an Integrated Approach

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).

Linkages between GHG mitigation and other policy areas can be taken into account when designing different types of policies such as economic instruments, regulatory policies, voluntary agreements, and awareness and education strategies. Policies targeting economic activities (e.g., combustion of fossil fuels, intensive agriculture) rather than the emissions of one specific substance (like carbon dioxide, sulphur dioxide, or ammonia) have a larger potential for capturing possible synergies.

In 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

In contrast to the TAR, where assessments of mitigation and adaptation were strictly separated, AR4 makes thorough efforts to explore the linkages between these two major domains of response to climate change. Chapter 18 in WGII is specifically devoted to mitigation-adaptation linkages and serves as the main reference for concepts, definitions, and analytical frameworks. This section explores the issues pertaining to mitigation from the cross-sectoral perspectives.

WGII Chapter 18 uses the TAR definitions of mitigation and adaptation and lists a number of linkages and differences between the two domains. Linkages go both directions and can be positive or negative. Depending on the socio-economic and geographical conditions, mitigation efforts can promote adaptive capacity in general and enhance the prospects for specific adaptation measures in a given sector or region, but they might also impair adaptive capacity, make adaptation more difficult or foreclose some adaptation measures altogether. Similarly, some adaptation strategies entail GHG emission reductions directly or indirectly whereas others might increase emissions.

The most important difference concerns timing. Earlier sections of this chapter denote a broad consensus that at least some form (technological development, direct emission reduction) and level (modest to more ambitious) of mitigation is required in the near term. In contrast, the need for adaptation to climate change impacts will gradually emerge over the coming decades with the exceptions. First, the need for reducing the sensitivity to climate change impacts and enhance the adaptive capacity of currently vulnerable sectors and societies (largely congruent with the criteria for sustainable development). Second, the need to take into account for climate change impacts in designing new and refurbishing existing long-lasting infrastructure (coastal defence, sea ports, bridges, river flood protection and dams, etc.). It follows from the above that in the near term, the implications of some mitigation actions for adaptation dominate the scene, particularly renewable energy from land-based biomass, considered below.

Over the medium and long term, it will be important to consider linkages in both directions. Earlier in this chapter, the importance of technological development has been discussed. The mitigation-adaptation linkage implies that, in addition to the standard technological assessment criteria, new mitigation technologies should be assessed with a view to their implications for climate change adaptation and adaptive capacity in general. In the opposite direction, many adaptation strategies involve increasing energy use (agriculture, air conditioning) and therefore need to be evaluated in terms of the associated energy technologies and GHG emissions.

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. 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 et. al., 2002; Murdiyarso, et. al., 2004).

11.9.1 Dynamics of Decision Making, Probabilities, Uncertainty, Inertia, and Possible Impact of Surprises

In framing discussions on the risk, uncertain consequences and impacts of climate change, there is considerable literature available on how best to manage the climate change risk (Obersteiner, et. al., 2001), but with few simple solutions – most peer-reviewed articles point to the complexities of the issue , particularly in the area of whether and how policy makers decide the extent to which they should focus on adaptation or mitigation measures in their particular national contexts.

The majority of the literature accepts the definitions promoted through the IPCC and the UNFCCC on adaptation and mitigation namely that "mitigation is referred to…as the human capacity to reduce the root of the problem (e.g., by reducing GHG emissions or by enhancing sinks), whereas adaptation refers to the ability of systems (human and natural) to adjust (advertently or inadvertently) to climate change" (Dessai and Hulme, 2003)[7]. In other words, the decisions that policy makers must make to address climate change are most often cast in a non-zero sum game scenario – the extent to which resources are focused on mitigation (or vice versa) will have an impact on the resources available for the alternative policy response. This becomes increasingly more problematic when trying to calculate the impacts of Annex B Parties (under the Kyoto Protocol) taking the lead to reduce their overall greenhouse gas emissions – if achieved, will it work to actually incentivise reductions from other major emitters in a future regime beyond the Kyoto time frame and will it be in time? These are calculations clearly based on political intuition more than scientific analysis, but the sooner policy directions are clarified and agreed, on a global scale, regarding mitigation objectives, the sooner analysts will be able to provide estimates on the impacts of future global climate change.

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.

Complicating factors include the imprecision of determining impacts on a global and regional scale, the timing of those impacts and the fact that mitigation provides a global benefit while adaptation is local in its effects (Dang, *et al.*, 2003). In addition, fundamental differences between adaptation and mitigation are noted, including the relatively long time it takes for mitigation to take effect (given the long residence time of most GHGs in the atmosphere) versus the more immediate impacts of adaptation; the relatively clearer picture of the costs and benefits of mitigation versus greater uncertainties involved in costing out impacts and benefits; and, the qualitative differences between mitigation and adaptation on the actors and policies involved in implementing the different set of policies.

As a result, at the national level, mitigation and adaptation are often cast as competing priorities for policy makers. (Michaelowa, 2001; Cohen et. al., 1998). 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. Societal pressure for adaptation will depend on the occurrence of extreme weather

[7] Less clear is the definition around the phrase 'adaptive capacity' – the majority of the literature by climate change experts usually define it as the capacity to adapt to the impacts of climate change, while literature focusing on the broader question of complex management/policy systems typically refer to this phrase as the capacity of relevant actors to respond, in toto, to a specific issue. In the case of climate change, therefore, this definition would cover the capacity of relevant actors to respond, addressing both adaptation and mitigation activities.

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, et. al., 2002). 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. forthcoming), on forestry, on agriculture (Dang *et al.* 2003), and on coastal systems (Ehler, 1997).

11.9.2.1 Renewable energy from biomass and agroforestry

Large-scale expansion of land-based renewable energy sources is constrained under the Marrakesh Accords. 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 (Bernes et al, 2001) and that the productivity of land is as important as its absolute supply: there is no shortage of land (Moreira, 2005; Bot et al, 2000), 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 (Read, 2005; Greene et al, 2004; Faaij, 2005; Lehmann et al, 2005; 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.

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