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Issues related to mitigation in the long-term context

Contents

Executive summary

This chapter first documents new baseline and stabilization scenarios in the literature since the publications of the IPCC Special Report on Emissions Scenarios (SRES, Nakicenovic *et al.*, 2000) and Third Assessment Report (TAR, Morita *et al.*, 2001). It reviews the use of the SRES reference and TAR stabilization scenarios and compares them with new scenarios that have been developed by the modeling community during the last five years. Of special relevance is a how representative the SRES ranges of driving forces and emissions are of the newer scenarios in the literature. Other important aspects of this review include methodological, data and other advances since the time the SRES scenarios were developed. The focus of the chapter is on scenarios that stabilize atmospheric concentrations of GHG and other relevant anthropogenic substances that are radiatively active in the atmosphere such as sulfur aerosols. New multigas stabilization scenarios represent a significant change in the new literature compared to TAR.

The main finding from the comparison of SRES and new scenarios in the literature is that the uncertainties as represented by the ranges of main driving forces and emissions have not changed very much. The main change is that population projections are now generally lower, but they have not been fully implemented so far in the emissions scenarios in the literature. However, this will have to be considered in any new scenario exercise. Economic growth perspectives have not changed much even though they are among most intensely debated aspects of SRES scenarios. In particular, very few of the new scenarios are calibrated in purchasing power parities (PPP) so that most of the literature (more than 99 per cent of all scenarios in the literature) is still based on market exchange rates. There have been some changes in the distribution of the carbon dioxide emissions. There are now more scenarios that explore both the upper and the lower of the SRES emissions changes. There are also many more new scenarios that include all gases and not only carbon dioxide.

3.1 Emissions scenarios

Future greenhouse gas emissions and the evolution of their underlying driving forces are highly uncertain. This is reflected in the very wide range of future emissions paths in the literature. There are more than 600 emissions scenarios in the literature. Most of them are documented in the scenario database originally developed for the IPCC Special Report on Emissions Scenarios (SRES, Nakicenovic *et al.*, 2000) that has been extended to include the most recent scenarios in the literature.[1] This chapter assesses the new scenarios in the literature since the publication of SRES (Nakicenovic *et al.*, 2000) reference scenarios and TAR (Morita *et al.*, 2001) mitigation scenarios. Particular focus of this emissions scenario assessment is on the new multigas stabilization scenarios.

The IPCC SRES set of reference scenarios was representative of some 500 emissions scenarios in the literature at the time of its approval by IPCC in 1999. SRES scenarios still span most of the range of socioeconomic driving forces and GHG emissions. They were developed by six different

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[1] The scenario database is accessible through the web site (www-eger.nies.go.jp).

integrated assessment models that covered the diversity of alternative methodological approaches from bottom-up to top-down approaches. SRES scenarios were not an end in it self but rather a part of the process. IPCC developed sets of emissions scenarios in 1990 (Houghton *et al.*, 1990) and 1992 (Leggett *et al.*, 1992; Pepper *et al.*, 1992). In 1994 the IPCC formally evaluated the 1992 scenario set (Alcamo *et al.*, 1995) and in 1996, it initiated the development of SRES scenarios that were published four years later. SRES scenarios were used very widely within the IPCC assessments and in the climate change research in general. For example, IPCC TAR based its climate change projections on SRES and developed a set of 80 scenarios with policies and measures directed at stabilizing CO_2 concentrations based on SRES (Morita *et al.*, 2001).

This chapter first documents new baseline and stabilization scenarios in the literature since the publications of SRES. We often refer to this literature as 'post-SRES' scenarios. The chapter reviews the use of the SRES reference and TAR stabilization scenarios and compares them with new scenarios that have been developed by the modeling community during the last five years. Of special relevance is a how representative the SRES ranges of driving forces and emissions are of the newer scenarios in the literature. Other important aspects of this review include methodological, data and other advances since the time the SRES scenarios were developed. The focus of the chapter is on scenarios that stabilize atmospheric concentrations of GHG and other relevant anthropogenic substances that are radiatively active in the atmosphere such as sulfur aerosols.

An important source of stabilization scenarios are modeling networks that were organized to assess various questions associated with multigas stabilization scenarios. In particular, this chapter uses the results of the Energy Modeling Forum (EMF-21) scenarios and the new Innovation Modeling Comparison Project (IMCP) network scenarios. In contrast to SRES and post-SRES scenarios, these new modeling comparison activities are not based on fully harmonized input assumptions but rather on 'modeler's choice' scenarios. Thus, the uncertainties are due both to different assumptions and different modeling approaches. Another further complication is that even baseline scenarios include some explicit policies directed at emissions reduction. Even at the time scenarios in the literature were assessed within SRES, it was not always possible to clearly differentiate between the baseline scenarios and those that include climate-related policies. This is becoming ever more difficult with Kyoto entering into the force and other climate-related policies that are being implemented in many parts of the world. Some of the new reference scenarios in the literature include such policies and measures as the integral component of the baseline assumptions.

The main finding from the comparison of SRES and new scenarios in the literature is that the uncertainties as represented by the ranges of main driving forces and emissions have not changed very much. The main change is that population projections are now generally lower, but they have not been fully implemented so far in the emissions scenarios in the literature. However, this will have to be considered in any new scenario exercise. Economic growth perspectives have not changed much even though they are among most intensely debated aspects of SRES scenarios. In particular, very few of the new scenarios are calibrated in purchasing power parities (PPP) so that most of the literature (more than 99 per cent of all scenarios in the literature) is still based on market exchange rates. There have been some changes in the distribution of the carbon dioxide emissions. There are now more scenarios that explore both the upper and the lower of the SRES emissions changes. There are also many more new scenarios that include all gases and not only carbon dioxide.

3.1.1 The purpose and definition of scenarios

Scenarios describe possible future developments. They capture how main driving forces underlying the salient future developments might evolve, interact with each other and how they might be affected by policy interventions. Scenarios serve different purposes and are context specific. Often scenarios come as a set of alternatives.

They can be used in an explorative manner or for a scientific assessment in order to understand the functioning of an investigated system (Alcamo *et al.*, 2005, MA forthcoming). Researchers are often interested in exploring hypothesized interactions and linkages between key variables by using scenarios analysis. On the other hand scenarios can be utilized as part of a decision-making or planning process and for bridging the gap between the scientific and the policy-making communities. In this case upcoming decisions need to be highlighted and different choices and their outcomes can be explored. Here the scenarios can be used either in a more informative or educational way. Or, depending on the process employed, they can lead to challenging assumptions on the functioning of certain processes (Davis 2002) and illustrate different views on their outcomes held by participants of the scenario building exercise (Alcamo *et al.*, 2005, MA forthcoming).

In the context of the IPCC assessments, scenarios are directed at exploring possible future emissions paths, their main underlying driving forces and how these might be affected by policy interventions. The IPCC evaluation of emissions scenarios in 1994 identified four main principal purposes of emissions scenarios (Alcamo *et al.*, 1994):

- To provide input for evaluating climatic and environmental consequences of alternative future GHG emissions in the absence of specific measures to reduce such emissions or enhance GHG sinks.
- To provide similar input for cases with specific alternative policy interventions to reduce GHG emissions and enhance sinks.
- To provide input for assessing mitigation and adaptation possibilities, and their costs, in different regions and economic sectors.
- To provide input to negotiations of possible agreements to reduce GHG emissions.

The SRES emissions scenarios were intended for the first, third and fourth uses. They do not include any additional (explicit) policies or measures directed at reducing GHG sources and enhancing sinks. However, the SRES reference scenarios do include a host of other policies and measures that are not directed at reducing sources and increasing sinks of GHGs, but that nevertheless have an indirect effect on future emissions. For example, policies directed at achieving greater environmental protection may also lead to lower emissions of GHGs. Moreover, afforestation and reforestation measures increase CO_2 sinks, and a shift to renewable energy sources reduces the sources of emissions. Subsequently, SRES scenarios were used as reference cases for the introduction of specific policy interventions and measures to achieve atmospheric stabilization of CO_2 concentrations in 80 TAR scenarios. These mitigation scenarios share with SRES the same specifications for the other principal driving forces of future emissions.

There are many definitions of scenarios in the literature. They differ a lot depending on the purpose of the scenarios and how they were developed. For example, SRES report (Nakicenovic *et al.*, 2000) defines a scenario as a plausible description of how future might develop, based on a coherent and internally consistent set of assumptions (‘scenario logic’) about the key relationships and driving forces (e.g. rate of technology changes or prices). The SRES report defines the whole set of scenarios as ‘alternative images of the future’ used to explore future developments (in greenhouse gas emissions and its driving forces). SRES scenarios consist of two integrated elements, qualitative narratives (or stories) about the future and quantitative elaborations of these stories, based on formal modeling. These two elements together define 'an internally consistent and reproducible set of assumptions' about key driving forces, relationships and outcomes.

The definition of scenarios in SRES differs from several alternative uses of scenarios found in the literature. For example, some studies in the literature apply the term 'scenario' to 'best-guess' or forecast types of projections. Such studies do not aim primarily at exploring alternative futures, but rather to identifying most likely outcomes. Probabilistic studies represent a different approach, in which the range of outcomes is based on a consistent estimate of the probability distribution function (pdf) for crucial input parameters. In these cases, outcomes are associated with an explicit estimate of likelihood, albeit one with a substantial subjective component. Examples include probabilistic projections for the population (Lutz *et al.*, 2001) and CO_2 emissions (Webster *et al.*, 2002; O'Neill, 2004). Other literatures include narrative scenarios often developed to provide plausible answers to the major uncertainties and focal questions about the future of socioecological systems or to challenge the prevailing mind sets.

3.1.1.1 Types of scenarios

Emissions scenarios in the literature span a wide range from narrative stories of future developments to quantitative model analyses. Often these two literatures have been separate with little if any overlap (Morita *et al.*, 2001). Figure 3.1 illustrates this heterogeneity of different scenarios in the underlying literature. The literature can be split into two largely non-overlapping streams - quantitative modelling and qualitative narratives. This dualism mirrors the twin challenges of providing systematic and replicable quantitative representation, on the one hand, and contrasting social visions and non-quantifiable descriptors, on the other (Ruskin *et al.*, 2005). A major methodological advance in scenario formulation process includes approaches that integrate narrative stories with quantitative model-based analysis. They are denoted in the Figure 3.1 by the overlapping area that encompasses both models and stories. The SRES scenarios include both storylines and quantifications.

[INSERT **Figure 3.1** here]

3.1.1.2 Narrative storylines and modeling

The literature based on narrative storylines or stories that describe futures is very rich going back to the first global studies of the 1970s (e.g. Kahn at al., 1976; Kahn and Wiener 1967) and is also well represented in more recent literature (e.g. Peterson, 1994; Hammond, 1998; Gallopin *et al.* 1997; Raskin *et al.*, 1998; Glenn and Gordon, 1997; Lawrence *et al.*, 1997). Well known are the Shell scenarios that are principally based on narrative stories with illustrative quantifications of salient driving forces and scenario outcomes (Wack 1985a; Wack 1985b; Schwartz, 1992; Davis, 2002).

Storylines can be provocative because they challenge the tendency of many people to extrapolate from the present into the future. They do this by describing divergent futures covering a significant portion of the underlying uncertainties in the main scenario driving forces. In this way they can be used to highlight key uncertainties and surprises about the future. Narrative stories can capture developments that cannot be modelled and they can serve to provide qualitative input for determining quantitative evolution of variables in integrated models. The differences among the storylines can cover a wide range of the key 'future' characteristics such as technology, governance, and behavioural patterns. This is why the plausibility or the feasibility of the storyline assumptions should be viewed with an 'open mind,' that is, not from a narrow interpretation of current situations and trends in economic conditions, technology developments and social and governing structures.

Catastrophic futures feature prominently in the narrative scenarios literature. They typically involve large-scale environmental or economic collapses, extrapolating current unfavourable conditions and trends in many regions.[2] Many of these scenarios suggest that catastrophic developments may draw the world into a state of chaos within one or two decades. Greenhouse-gas emissions might be low in such scenarios because of low or negative economic growth, but seem unlikely to receive much attention in any case, in the light of more immediate problems. Hence, this report does not analyze such futures.

3.1.1.3 Global futures scenarios

As mentioned, global futures scenarios are deeply rooted in the long history of narrative scenarios. The direct antecedents of contemporary scenarios lie with the future studies of the 1970s (Ruskin *et al.*, 2005). These responded to emerging concerns about the long-term sufficiency of natural resources to support expanding global populations and economies. This first wave of global scenarios included ambitious mathematical simulation models (Meadows *et al.*, 1972,; Mesarovic and Pestel, 1974) as well as speculative narrative (Kahn *et al.*, 1976). At this time, scenario analysis was first used at Royal Dutch/Shell as a strategic management technique (Wack, 1985; Schwartz, 1992).

During the early 1980s, a second round of integrated global analysis began in the late 1980s and 1990s, prompted by concerns with climate change and sustainable development. These included narratives of alternative futures ranging from 'optimistic' and 'pessimistic' worlds to consideration of 'surprising' futures (Burrows *et al.*, 1991; Milbrath, 1989; the Central Planning Bureau of the Netherlands, 1992; Kaplan 1994; Svedin and Aniansson, 1987; Toth *et al.*, 1989). The long-term nature of the climate change issue introduced a new dimension and has resulted in a rich new literature of global emissions scenarios, extending to the IPCC IS92 scenarios (Pepper *et al.*, 1992; Leggett *et al.*, 1992) and most recent scenario comparisons projects (e.g. EMF and IMCP). The first decades of scenario assessment paved the way by showing the power – and limits – of both deterministic modelling and descriptive future analyses. A central challenge of global scenario exercises today is to unify these two aspects by blending the objectivity and clarity of quantification with the richness of narrative (Ruskin, 2005).

3.1.1.4 Linking storylines to scenarios

Over the past decade, the global scenario analysis community has begun to combine the primarily qualitative and narrative-based scenario analyses undertaken by Royal Dutch/Shell and other companies (Wack 1985a; Wack 1985b; Schwartz 1992), with global modeling work in the form of analyses that combine the development of detailed narrative storylines with their 'quantification' in various global models (Raskin 1998; Nakicenovic *et al.* 2000). It is particularly noteworthy therefore, that recent developments in scenario analysis are beginning to bridge this difficult gap (Nakicenovic et. al., 2000; Morita *et al.* 2001; Swart and Ruskin. 2004; and Millennium Ecosystems Assessment scenarios (Alcamo *et al.*, 2005; MA, 2005, forthcoming). For example, the SRES

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[2] Prominent examples of such scenarios include the 'Retrenchment' (Kinsman, 1990), the 'Dark Side of the Market World' or 'Change without Progress' (Schwartz, 1991), the 'Black and Grey' (Godet *et al.*, 1994), the Global Incoherence Scenario (Peterson, 1994), the 'New World Disorder' (Schwartz, 1996), 'A Visit to Belindia' (Pohl, 1994), the 'Barbarization' (Gallopin *et al.*, 1997), 'Dark Space' (Glenn and Gordon, 1999), 'Global Fragmentation' (Lawrence *et al.*, 1997), and 'A Passive Mean World' (Glenn and Gordon, 1997 and 1999.

scenarios undertaken for the IPCC, cut across the interpretive/descriptive divide (See Figure 3.1), though still focusing mainly on the global and regional level.

The SRES scenarios were based on four alternative storylines of future developments of main driving forces that provided a consistent basis for scenario quantifications with six different integrated assessment models. Integration of storylines and model quantifications included:

- the nature of the global and regional demographic developments;
- the extent to which economic globalization and increased social and cultural interactions continue over the next century;
- the rates of global and regional economic developments and trade patterns;
- the rates and direction of global and regional technological change;
- the extent to which local and regional environmental concerns shape the direction of future development and environmental controls;
- the degree to which human and natural resources are mobilized globally and regionally to achieve multiple development objectives of each storyline; and
- the balance of economic, social, technological or environmental objectives in the choices made by consumers, governments, enterprises and other stakeholders.

3.1.2 Introduction to climate policy scenarios and stabilization metrics

Climate change intervention, control, or mitigation scenarios capture measures and policies for reducing GHG emissions with respect to some baseline scenario. They contain emission profiles as well as costs associated with the emission reduction. Some give explicit portfolio of mitigation technologies, other more aggregate emissions reduction profiles. Stabilization scenarios are mitigation scenarios that aim at a pre-specified GHG reduction target. Usually the target is the concentration of CO_2 or the CO_2-equivalent concentration of a 'basket' of gases (thus the name mulitigas) by 2100 or at some later date when atmospheric stabilization is actually reached (Morita *et al.*, 2001).

Mitigation scenarios are an essential tool for the assessment of policies and measures that would be required to reduce future GHG emissions. In this report, we use the terminology from the IPCC evaluation of emissions scenarios (Alcamo *et al.*, 1995) and SRES (Nakicenovic *et al.*, 2000). Those scenarios that include some form of policy intervention are referred to as intervention scenarios, such as the 80 TAR scenarios (Morita *et al.*, 2001), while those that do not assume any climate policy measures, such as the 40 SRES scenarios (Nakicenovic *et al.*, 2000), are referred to as non-intervention scenarios. In some cases, intervention scenarios go even further and investigate more radical emissions reductions required to stabilize atmospheric concentrations of these gases (in accordance with Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC, 1992)). As mentioned above, assessment of such stabilization scenarios is the focus of this chapter.

In the literature assessment we use a simple approach to identify intervention scenarios. According to this approach, a scenario is identified as an intervention scenario if it meets one of the following two conditions:

- it incorporates specific climate change targets, which may include absolute or relative GHG limits, GHG concentration levels (e.g., CO_2 stabilization scenarios), or maximum allowable changes in temperature or sea level; and
- it includes explicit or implicit policies and/or measures of which the primary goal is to reduce GHG emissions (e.g., a carbon tax or a policy encouraging the use of renewable energy).

Some scenarios in the literature are difficult to classify as intervention or non-intervention, such as those developed to assess sustainable development. These studies consider futures that require radical policy and behavioral changes to achieve a transition to a sustainable development path; Greenpeace formulated one of the first (Lazarus *et al.*, 1993). Such sustainable development scenarios are also included in this assessment of the scenario literature. Where they do not include the explicit policies as in the case of SRES scenarios, they can be classified as non-intervention scenarios. For example, the SRES B1 family of scenarios can be characterized as having many elements of sustainability transition that lead to generally low GHG emissions even though the scenarios do not include policies or measures explicitly directed at emissions mitigation.

In addition to these ambiguities what constitutes baseline scenarios without climate polices a new and emerging classification problem is that some climate policies are being increasingly adopted throughout the world. Ever since the Kyoto Protocol entered into force on 16 February 2005 policies directed at implementation of emissions reductions commitments by the Parties can no longer be considered to be additional climate policies and need to become part of a reference scenario. Thus, new problems are emerging as to how to define the baseline. Assume for example, that some studies try still to ignore such policies in their baseline. Others include ‘policies in place’ as part of their baseline. Not including existing policies might lead to an overestimation of costs. Moreover, not easy to separate climate polices from other policies anyway.

Another type of intervention or climate policy scenarios envision future ‘worlds’ that are internally consistent with desirable climate targets (e.g., a global temperature increase of no more than 1°C by 2100), and then work ‘backwards’ to develop feasible emission trajectories and emission driver combinations leading to these targets. Such scenarios, also referred to as ‘safe landing’ or ‘tolerable windows’ scenarios, imply the necessary development and implementation of climate policies, intended to achieve these targets in the most efficient way (Motia *et al.*, 2001).

Confusion can arise when the inclusion of ‘non-climate-related’ policies in a non-intervention scenario has the effect of significantly reducing GHG emissions. For example, energy efficiency or land use policies that reduce GHG emissions may be adopted for reasons that are not related to climate policies and may therefore be included in a NCP scenario. Such a non-intervention scenario may have GHG emissions that are lower than some intervention scenarios. The root cause of this potential confusion is that, in practice, many policies can both reduce GHG emissions and achieve other goals. Whether such policies are assumed to be adopted for climate or non-climate policy related reasons in any given scenario is determined by the scenario developer based on the underlying scenario narrative. While this is a problem in terms of making a clear distinction between intervention and non-intervention scenarios, it is at the same time an opportunity. Because many decisions are not made for reasons of climate change alone, measures implemented for reasons other than climate change can have a large impact on GHG emissions, opening up many new possibilities for mitigation (Morita et al, 2001).

3.1.3 Development trends and the lock-in effect of infrastructure choices

An important consideration in emissions scenarios is about the very nature of development process and whether and to what extent developing countries may reproduce the development paths of industrialized countries with respect to energy use and GHG emissions. For example, globalization and more affluent lifestyles favor energy intensive housing, mobility, leisure and consumption patterns. On the supply side, the share of less developed regions in the world production of highly energy and pollution intensive goods, such as steel and aluminum, has been consistently increasing.

While there seem to be no significant differences here between development paths followed by industrialized and developing countries, in the latter strong links among agriculture, forestry, rural-urban migration, energy use, and GHG emissions are still crucial today. Commercial energy demand/GDP elasticities in industrialized countries have first increased along successive stages of industrialization, with an acceleration during the fifties and sixties, but have sharply decreased since then, due to different factors: relative growth of services in GDP share, technical progress induced by higher oil prices and energy conservation efforts, among others.

In developing countries, as a major part of the needed infrastructure to meet development needs is still to be built, the spectrum of future options is considerably wider than in industrialized countries (e.g. on energy, see IEA, 2004). The spatial distribution of the population and economic activities is still not settled, opening the possibility of adopting urban/regional planning and industrial policies directed towards rural development and strengthening the role of small and medium cities, thus reducing the extent of rural exodus and the degree of demographical concentration in large cities. The large amount of natural resources available in developing countries could be tapped through the use of modern technology leading to more decentralized development patterns, as in the case of the huge opportunities supplied by the prospects of biotechnology. The main issue here is the magnitude and viability to tap the potential for technological 'leapfrogging' whereby developing countries can bypass dirty intermediate technology and jump straight to cleaner technologies. There are large technical possibilities for less energy intensive development patterns in the long run leading to low carbon futures in the South compatible with national objectives (see e.g. La Rovere et al, 2002).

On the other hand, the barriers to a more sustainable development in the South can hardly be underestimated, going from financial constraints to cultural behaviors in industrialized as in developing countries, including the lack of appropriate institutional building. One of the key findings of the reviewed literature is the long-term implications for GHG emissions of short and medium-term decisions about the building of new infrastructure, particularly in developing countries (see e.g. La Rovere and Americano, 2002; IEA, 2004). Follows a call to implementing the appropriate institutional mechanisms for decision-makers taking into account these implications and incentives for developing countries to embark on lower-carbon development pathways (Beg et al, 2002).

3.1.4 New theory of economic growth and convergence

Determinants of long-term GDP per capita are labor force and its productivity projections. Labor force utilization depends upon factors such as projections of working-age population, structural unemployment and hours worked per worker. Demographic change is still the major determinant of the baseline labor supply (Martins and Nicoletti, 2005). Long-term projections of labour productivity primarily depend upon the advance of the technological frontier.

The new or newly rediscovered growth theory of the 1980s and 1990s reiterated the view that knowledge is the only means of production that is not subject to diminishing returns (Marshall, 1890; Clark, 1923). It brought about a marked change in the analysis of aggregate production functions, examining production functions that show increasing returns because of an expanding stock of human capital and as a result of specialization and investment in 'knowledge' capital (Meier, 2001; Aghion and Howitt, 1998). According to this interpretation, economic 'catch-up' and convergence strongly depend upon the forces of 'technological congruence' and 'social capability' between the productivity leader and the followers (see the subsequent sub-section on institutional frameworks and Section 3.4 on the role of technological change, in this chapter).

The economic convergence literature has been using a standard neoclassical economic growth setup to discuss the question of future world per capita income distribution and productivity levels, following the methods first used by Solow (1956). Abramovitz (1986) and Baumol (1986) found evidence of convergence between the richest countries, but not for the world as a whole. Other research efforts documented 'conditional convergence', meaning that countries appeared to reach their own steady states at a fairly uniform rate of 2 per cent per year (Barro, 1991; Mankiw et al, 1992). Jones (1997) found that the future steady-state distribution of per capita income will be broadly similar to the 1990 distribution. Important differences would continue to arise among the bottom two-thirds of the income distribution, confirming the trend observed since the sixties. Jones` analysis also highlighted the importance of total factor productivity (TFP) levels and convergence for the evolution of income distribution. Catch-up, and even overtaking in per capita incomes, as well as changes in leaders in the world distribution of income are among some of the expected findings in this literature. However, limits to this convergence are also highlighted. Quah (1993, 1996) found that the world is moving towards a bimodal income distribution. Jones` model results about the future steady-state distribution of per capita income levels indicate additional divergence at the bottom and convergence and overtaking at the top. Countries in the upper half of the world income distribution are expected to feature additional catch-up to the United States (with several economies overtaking the U.S. levels) while the other economies would remain close to their relative income levels (Jones, 1997).

Convergence is limited by a number of reasons, such as imperfect mobility of factors (notably labour); different endowments (notably human capital); market segmentation (notably services); and limited technology diffusion (different incentives). Therefore only limited catch-up can be factored in baseline (no-policy) scenarios: while capital quality is likely to push up productivity growth in most countries, especially in those lagging behind, labour quality is likely to drag down productivity growth in a number of countries, unless there are massive investments in education. However, appropriate policies may play an important role to accelerate the convergence process, creating incentives for human capital formation and to adopt new technologies (Martins and Nicoletti, 2005).

The assumptions of SRES scenarios about world income convergence were found to be consistent with historical evidence for regional income convergence in OECD regions (Barro and Sala-i-Martin, 1997; Riahi, 2005). The annual rate of income convergence between 11 world regions in SRES scenarios falls within the range of less than 0.5 per cent in A2 to less than 2.0 per cent in A1 (both in purchasing power parity and market exchange rate metrics). In the period 1950-1990, 90 regions in Europe have shown annual rate of income convergence close to 2 per cent. An important finding from the sensitivity analysis performed is that less convergence generally yields higher emissions. In B2, an income ratio (between 11 world regions, in MER) of 7 corresponds to CO_2 emissions of 14.2 GtC in 2100, while shifting this income ratio to 16 would lead to CO_2 emissions of 15.5 GtC in 2100. Results pointing to the same direction were also obtained for A2. This can be explained by slower TFP growth, slower capital turn over, and less 'technological congruence' leading to slower adoption of low emissions technologies in developing countries. On the other hand, as climate stabilization scenarios require global application of climate policies and convergence in adoption of low emissions technologies, they are less compatible with low economic convergence scenarios (Riahi, 2005).

3.1.5 Development paths in the context of mitigation

Over the long run, the links between economic development and GHG emissions depend not only on the rate of growth (measured in aggregate terms), but also on the nature and structure of this growth. Comparative studies aiming to explain these differences help us understand the main factors that will ultimately influence the amount of GHG emissions, given a certain overall rate of economic growth (Jung et al, 2000):

- structural changes in the production system, namely the role of high or low energy-intensive industries and services: the energy content of industries such as steel, non ferrous metals, heavy chemistry and pulp and paper is between four and six times the energy content of the other industries.
- technological patterns in sectors such as energy, transportation, building, agriculture and forestry: the treatment of technology in economic models has so far received most of the efforts and triggered the most difficult debates within the community of economic modelers (Edmonds and Clarke, 2005; Grubb et al, 2005; Shukla, 2005; Worrell, 2005).
- geographical distribution of activities: the geographical distribution encompasses both human settlements and urban structures in a given territory, and has a twofold impact on the evolution of land uses, and on mobility needs and transportation requirements.
- consumption patterns: existing differences between countries are mainly due to inequalities in income distribution, but for a given income per capita, parameters such as housing patterns, leisure styles, or the durability and rate of obsolescence of consumption goods will have a critical influence on long-run emission profiles.
- trade patterns: the degree of protectionism and the creation of regional blocks can influence the access to the best available technologies, inter alia, and constraints on financial flows can limit the capacity of developing countries to build their infrastructure.

These different relationships between development pathways and GHG emissions may or may not be captured in models used for long-term world scenarios, by changes in aggregated variables such as per capita income or through more disaggregated economic parameters, e.g., the structure of expenses devoted to a given need such as heating, transport or food, or the share of energy and transportation in the production function of industrial sectors. This means that alternative configurations of these underlying factors can be combined to give internally consistent socioeconomic scenarios with identical rates of economic growth. It would be false to say that current economic models ignore these factors. They are to some extent captured by changes in economic parameters, such as the structure of household expenses devoted to heating, transportation or food; the share of each activity in the total added value; and the share of energy and transportation costs in the production function of industrial sectors.

These parameters remain very important indeed, but the outcome in terms of GHG emissions will also depend upon dynamic linkages between technology, consumption patterns, transportation and urban infrastructure, urban planning, and rural-urban distribution of population. The lack of knowledge available about their dynamic linkages and about their interactions with economic policies over the long run must be underlined together with the intrinsic difficulty of predicting innovations and transformation of lifestyles in the long term.

3.1.6 Institutional frameworks

Institutional frameworks are referred to as qualitative driving forces, since their manifestations are diverse and are not readily measurable in quantitative terms. Interventions that alter institutional structure are among the most accepted solutions in recent times for shaping economic structure and its associated energy use and emissions. Three important aspects of institutional structure are 1) the extent of centralization and participation in decisions, 2) the extent (spanning from local to global) and nature of decision mechanisms, and 3) processes for effective interventions (e.g., the mix of market and regulatory processes). In these regard, the institutional structures vary considerably across nations with similar levels of economic development, despite vast differences between industrialized and developing nations. The importance of understanding institutional structure lies in the fact that design of effective institutions are often a means for achieving goals such as national economic development and mitigation of climate change. Although no consensus exists on the desirability of a specific type of institutional framework, experience suggests that more participative processes help to build trust and social capital to better manage the environmental 'commons' (Beierle and Cayford, 2002; Ostrom *et al.*, 2002; Rydin, 2003; NAS forthcoming). Other relevant developments may include greater use of market mechanisms and better global coordination to enhance the ability of institutions to effectively manage global environmental issues (see Ch. 12).

Recent development research has included studies on the role of institutions as a critical component in an economies capacity to use resources optimally. Institutions are here in a broad sense being understood as the core allocation mechanism and as the structure of society that organizes markets and other institutions (Peet and Hartwich, 1999). A weak institutional structure on one hand basically explains why an economy can be in a position that is significantly below the theoretically efficient production frontier. Several economists suggest that the institutional structure can be understood as the so called 'missing link' in the production function that explains differences in economies productive capacity (Meier, 2001). Furthermore weak institutions also provide a basis for high transaction costs because frictions in economic exchange processes arrive when institutions are weak.

This understanding of institutional mechanisms has wide policy implications. The policy implication is i.e. formulated by Oliver North as there is no greater challenge than forming a dynamic theory of social change than enables an understanding of an economy's 'adaptive efficiency', by which North means a flexible institutional matrix that adjusts to technical and demographic change as well as to shocks to the system (after Peet and Hartwick, 1999). The policy recommendation that follows is to enhance institutions like the financial sector, information and risk sharing, as well as general market development. Institutional innovation is a key to reduce the gap to the production frontier (due to some inefficiency in the use of available resources) that can be verified in all economies, and particularly in developing countries.

Weak institutions in developing countries have a lot of implications for the capacity to adapt or mitigate to climate change. A review of the social capital literature and the implications for climate change mitigation policies concludes that successful implementation of GHG emission reduction options in most cases will depend on additional measures to increase the potential market and the number of exchanges. This can involve strengthening the incentives for exchange (prices, capital markets, information efforts and the like), introduction of new actors (institutional and human capacity efforts), and reducing the risks of participating (legal framework, information, general policy context of market regulation). The measures all depend on the nature of the formal institutions, the social groups of society, and the interaction between them (Halsnæs, 2002).

Some of the climate change policy recommendations that are inspired by institutional economics include general capacity building programmes, and local enterprise and finance development for example in the form of soft loans, in addition to educational and training programmes (Halnaes et al, 2003).

In the presently less industrialized regions, there is a large and relatively unskilled part of the population which is not yet involved in the formal economy. In many regions industrialization leads to wage differentials which draw these people into the more productive, formal economy, in the process causing accelerated urbanization. This is why labour force growth in these regions contributes significantly to GDP-growth. The concerns relating to the informal economy are twofold: 1) whether historical development patterns and relationships among key underlying variables will hold constant in the projections period, and 2) whether there are important feedbacks between the evolution of a particular sector and the overall development pattern that would affect GHG emissions (Shukla, 2005).

Social and cultural processes influence the future in a myriad of ways. They shape the institutions and how they function. Social norms of ownership and distribution have a vital influence on the structure of production and consumption. And most vitally, the social and culture processes determine the quality and extent of the so-called social 'infrastructure' sectors, such as education, which is paramount to capacity building and technological progress. Unlike institutions, social and culture processes are often more inflexible and difficult to influence. However, specific sectors like education are amenable to interventions. Barring some negative features, such as segregation for instance, there is no consensus as to the interventions that are necessary or desirable to alter social and cultural processes. On the other hand, understanding their role is crucial for assessing the evolution of the social infrastructures that underlie technological progress and human welfare (Jung et al, 2000) as well as evolving perceptions and social understanding of climate change risk (e.g. Rayner and Malone, 1998; Douglas and Wildavsky, 1982; Slovic, 2000).

3.2 Baseline scenarios

3.2.1 Drivers of emissions

3.2.1.1 Population projections

3.2.1.1.1 Recent projections for the medium term

Current population projections anticipate less global population growth than was expected at the time the Third Assessment Report (TAR) was published and are generally lower than the projections used in the SRES scenarios. The SRES emissions scenarios use three population projections produced in 1996 by the UN (UN, 1998, for the B2 scenario) and the International Institute for Applied Systems Analysis (IIASA) (Lutz *et al.*, 1996, for the A1/B1 and A2 scenarios). These scenarios were consistent with the demographic outlook at that time (Gaffin, 1998), spanning approximately the 90 per cent uncertainty interval associated with the IIASA probabilistic projections at the global level, a level just within the 5th and 95th percentiles of the distribution.

However since the early 1990s demographers have revised their outlook on future population downward toward smaller, older populations, based mainly on new data indicating that birthrates in many parts of the world have fallen sharply. For example, Figure 3.2a compares the projections for 2050 used in SRES to the most recent projections from IIASA (Lutz *et al.*, 2001), UN (2005), World Bank (2005) and US Census Bureau (2005) for the world and the four SRES macro regions. For comparability, the figure plots all population sizes relative to the projected population in the SRES B2 scenario for each region i.e. the UN medium scenario produced in 1996.

For the world as a whole, population was projected to be 9.4 billion in 2050 in the SRES B2 scenario. The A2 scenario anticipated a 21 per cent higher global population of 11.3 billion, and the A1 and B1 scenarios a 7 per cent lower population of 8.7 billion. Recent projections indicate a small downward revision to the medium (or 'best guess') outlook and to the high end of the uncertainty range, and a larger downward revision to the low end of the uncertainty range (van Vuuren and O'Neill, in press). As a group, updated medium projections for the world foresee 0.1 to 0.6 billion (1 to 6 per cent) fewer people than in the SRES B2 projection. Similarly, updated high scenarios from the UN and IIASA anticipate 0.5 to 0.7 billion fewer people than the high population scenario assumed in SRES A2. Updated low scenarios differ more sharply from the SRES assumptions, anticipating 1.0 to 1.7 billion fewer people relative to the low scenario used in the SRES A1 and B1 scenarios.

Extending this comparison to the level of the four SRES macro regions shows that Asia and ALM drive the global results. Asia and ALM display a similar pattern of change, a large downward revision to the low end of the uncertainty range and a smaller revision to the medium and high end. These changes are primarily due to shifts in the outlook for Sub-Saharan Africa, the Middle East and North Africa region, and the East Asia region, where recent data shows lower than expected fertility rates in these regions as well as a much more pessimistic view on the extent and duration of the HIV/AIDS crisis in sub-Saharan Africa.

In contrast, in the OECD region updated projections are somewhat higher than previous estimates, despite continuing low fertility in these regions. The new projections are higher due to changes in assumptions regarding migration in the case of the UN projections, or to a more optimistic projection of future life expectancy in the case of IIASA projections. In the REF region, projections have been revised downward, especially by the UN, driven mainly by recent data showing very low fertility levels and mortality that is quite high relative to other industrialized countries.

It should be noted that the SRES A1/B1 assumptions for the industrialized countries (OECD and REF regions) cannot be directly compared to the low-end range of more recent scenarios, because SRES did not assume a low population growth projection for these regions, even though growth was relatively low in A1/B1 for the world as a whole. Rather, SRES assumed a medium fertility scenario coupled with relatively low mortality in these regions, which in combination resulted in a future growth that was actually somewhat high relative to a 'best guess' projection.

[INSERT **Figure 3.2** here]

3.2.1.1.2 Recent long term population projections

IIASA (2001) and the UN (2004) are the only institutions that have produced updated projections for the world that extend to 2100, shown in comparison to the SRES assumptions in Figure 3.2b. Patterns are qualitatively similar to those found for 2050, but larger in magnitude. In additional, there is a general downward shift in the full range of projections that is somewhat larger at the lower end. For example, the most recent central projections for global population are 1.4 to 2.0 billion (13 to 19 per cent) lower than the medium population scenario of 10.4 billion used in the SRES B2 scenarios. Similarly, the SRES A2 population assumption of 15 billion in 2100 is now 1.1 to 1.7 billion above the UN high scenario and IIASA 95th percentile. At the low end differences are larger. The UN low scenario and IIASA 5th percentile are 1.6 to 2.2 billion below the SRES A1/B1 assumptions.

As was the case with the outlook for 2050, the long term changes at the global level are driven by the developing country regions (Asia and ALM), with the changes particularly large in China, the Middle East and North Africa, and Sub-Saharan Africa.

3.2.1.1.3 Population projections used in recent emissions scenarios

Figure 3.3 compares population projections used in emissions scenarios published since TAR to those used in emissions scenarios that appeared in or before TAR. The most notable result of this comparison is that the range of population projections used since TAR has not changed substantially, despite the downward trend in new population projections in the demographic literature. The median of post-TAR population assumptions (10 billion) is only slightly below the TAR and pre-TAR median of 10.4 billion, and 90 per cent of the population scenarios in both the pre and post-TAR distributions fall between a global population of 7 and 15 billion in 2100.

[INSERT **Figure 3.3** here]

One reason for this result is that most emissions scenarios in the literature continue to use the population assumptions employed in the SRES scenarios, or quantitatively similar projections. They have yet to adopt the lower range of projections found in recent projections by demographic institutions.

Although the range of projected population sizes has shifted down since the development of the SRES scenarios, this does not automatically imply that the SRES population assumptions are no longer credible. For example, the assumptions used in the SRES B2 and A1/B1 scenarios still fall within the plausible range of population outcomes according to more recent literature (see Figure 3.2). What is clearly under-represented, however, in SRES and more recent emissions scenarios are population assumptions at the low end of the current range. In addition, the high end of the range of population assumption in SRES and more recent emissions scenarios now fall above recent projections from IIASA and the UN. This is a particular problem for population projections in East Asia, the Middle East, North Africa and the Former Soviet Union, where the differences are large enough to strain credibility, and the use of revised projections is recommended if possible (van Vuuren and O'Neill, in press). Potential revised population scenarios include those specifically designed to be consistent with SRES storylines, including a new A2 scenario (Gruebler *et al.*, in prep.), and a set of alternative demographic outcomes for all SRES storylines (Hilderink, 2004).

3.2.1.2 Economic development

Economic activity is a dominant driver of energy demand and thus of emissions of greenhouse gases. Economic activities take many forms, from extraction of various raw materials, through manufacturing of physical goods, to provision and use of a broad range of services. Each of these activities requires input of energy and leads to emissions of a broad range of substances, including greenhouse gases (GHGs). These activities measured in their own (physical) units are the real drivers of emissions. However, in models, in analysis and certainly for reporting purposes, the activities need to be aggregated. Aggregation is generally done by converting activities into monetary units through the use of a set of observed market prices. For long-term scenarios, economic growth is usually reported in the form of growth of Gross Domestic Product (GDP) or Gross National Product (GNP). To get a meaningful comparison over time of the real size of economic activities, changes in price levels must be taken into account and corrected for by reporting activities in constant prices taken from a base year. The actual numbers reported and the time series obtained will of course depend on which base year is chosen. One way of reducing the effects of differences in base year employed in different studies is to report only growth rates in activity levels. Therefore, in the following we will focus on growth rates rather than the absolute numbers.

Another difficulty arises when economic activity data is compared or aggregated across nations or world regions, namely how to convert from one monetary unit to another. Here there are mainly two possibilities: the observed market exchange rate (MER) in a fixed year, or the Purchasing-Power-Parity (PPP) index (see Box 3.1).

Box 3.1.

For international comparison, GDP data must be converted into a common unit. The conversion can be based on observed market exchange rates (MER) or Purchasing-Power-Parity estimates (PPP), in which a correction is made for differences in price levels among countries. PPP is currently considered to be the better alternative if data are used for welfare or income comparisons across regions. PPP exchange rates are derived through a process of equalizing the purchasing power of different currencies by eliminating differences in price levels for various goods. As one example, if the price of a hamburger is US$2.20 in the United States and 60 rupees in India, then the PPP exchange rate for hamburgers between the two currencies can be calculated as 60/2.2, or 27.3 rupees to the dollar. Similarly, the concept of PPP for one good can be generalized to various baskets of goods and services in different countries to derive PPP rates for converting aggregate national income and product accounts to U.S. dollars. Usually, market exchange rates under-value the purchasing power of currencies in the poor part of the world.

Clearly, derivation of PPP exchange rates requires analysis of a relatively large amount of data. This makes it impractical to derive PPP rates for every year. Hence, methods have been devised to derive PPP-rates for new years on the basis of price indices. Unfortunately, there is currently no single method or price index favoured for doing this, resulting in different sets of PPP rates (e.g. from the OECD, Eurostat, World Bank and Penn World Tables). Furthermore, scenarios expressed in PPP numbers are relatively few. This creates some practical difficulties in reporting economic scenarios based on PPP exchange rates and is one reason why economic scenario data are generally reported in MER numbers – although for some models, also PPP-based values are given.

GDP trajectories in the large majority of scenarios in the literature are calibrated in MER. A few dozen scenarios exist in the literature that use PPP exchange rates, but most of them are shorter-term, generally running out to 2030.

3.2.1.2.1 GDP growth rates in the new literature compared to SRES

Many of the long-term economic projections in the literature have been specifically developed for climate-related scenario work. Figure 3.4 compares the range of the 151 scenarios from the literature pre-TAR and pre-SRES with the 283 new scenarios developed post-TAR. While there is a considerable overlap in the GDP numbers published, perhaps the most interesting difference is that some of the highest scenarios in the pre-SRES and TAR literature are not mirrored anymore in the new scenario literature. The data suggests that the upper-most range of economic growth has been adjusted downward in the current projections. It should be noted, however, that this is mainly due to a small group of very high growth scenarios. Changes in the mean are much less noticable.

[INSERT **Figure 3.4** here]

A comparison of the SRES scenarios within the range consistent with the GDP projections used pre-TAR to the recent short-term GDP projections is illustrated in Figure 3.5 (see also Van Vuuren and O'Neill). The SRES scenarios project a very wide range of global economic growth rates from 1.0 per cent (A2) to 3.1per cent (A1), both based on MER. This range is somewhat wider than the range covered by the USDOE high and low scenarios (1.2 to 2.5 per cent). The central projections of USDOE, IEA and World Bank all note growth rates of around 1.5 to 1.9 per cent, thus occurring in the middle of the range of the SRES scenarios, near the B2 trajectory. Other medium-term energy scenarios are also reported to have growth rates in this range (IEA, 2004). It should be noted that although the SRES A1 scenario lies outside the range of the scenarios included here, it is equal to USDOE's 2003 high-growth projection.

On the regional scale, the range of the SRES scenarios is still generally consistent with the more recent studies, but there are some important differences. For the OECD and the REF regions, the correspondence between SRES outcomes and recent scenarios is relatively good, although the SRES GDP growth rates are somewhat conservative. In the ASIA region, the SRES range and its median value have a small upward bias compared to recent studies. The differences between the SRES outcomes and more recent projections are largest in the ALM region. Here, the A1 and B1 scenarios clearly lie above the upper end of the range of current projections (4 to 5 per cent), while A2 and B2 fall near the centre of the range (1.4 to 1.7 per cent). The recent short-term projections used here expect current barriers to economic growth in these regions to slow down growth, at least until 2015. Projections from SRES scenarios other than the marker in each family contain somewhat lower growth rates for A1 and B1.

[INSERT **Figure 3.5** here]

3.2.1.2.2 Critique of the use of MER in the SRES

Recently, the uses of MER-based economic projections in SRES have been criticized (Castles and Henderson, 2003a,b; Henderson, 2004). It should be noted that the vast majority of scenarios published in literature are using MER-based projections. Some exceptions exist such as recent scenarios with the MERGE model (Richels and Manne, 2003) or shorter-term scenarios going to 2030 including the IEA World Energy Outlook (WEO, 2004). The main criticism of the MER based models is that the GDP for world regions covered in the models are derived using market exchange rates (MER) and were not corrected with respect to purchasing power parities (PPP) in most of the model runs. The consequence is that the economic activity levels in non-OECD countries generally appear to be lower than they actually are when measured in PPP units. In addition, the SRES scenarios assume that regions tend to partially converge in terms of relative per capital income across regions. The use of MER and the assumption of convergence combined leads to overstated economic growth in the poorer regions, and accordingly excessive growth in energy demand and emission levels, according to the critics. A team of SRES researchers has responded to this criticism, indicating that in their view, the use of MER or PPP data does not in itself lead to different emission projections outside the range of the literature, and that the use of PPP data was at the time (and probably still is) impossible due to lack of existing projections (Nakicenovic *et al.*, 2003, Grübler *et al.*, 2004). Also other researchers have indicated their opinion on this issue or explored it in a more quantitative sense (e.g. Manne and Richels, 2003, and McKibben *et al.*, 2004a,b, Holtsmark and Alfsen, 2004a, b).

There are at least two strands to this debate. On the one hand there is the question of whether economic projections based on MER are appropriate, and thus whether the economic growth rates reported in the SRES and other MER-based scenarios are reasonable or even believable. On the other hand, there is the question of whether the choice of MER versus PPP as exchange rate metric influences the projected emission levels.

On question of whether PPP or MER should be employed in economic scenario works, the debate at the moment seems to be fully open – with both theoretic and pragmatic considerations playing a role. Nordhaus (2005) recommends, for principle and practical reasons, that economic growth scenarios should be constructed by using regional or national accounting MER-based figures (including growth rates) for each region, but using PPP exchange rates for aggregating regions. According to Nordhaus, the PPP rates should be updated over time by use of a superlative price index, for instance the Törnqvist index. In contrast, Timmer (2005) actually prefers the use of MER-data in long-term modeling as data is better available, and many international relations within the model are based on MER.

When it comes to the emission projections, it is not as likely that the choice of exchange rate will have a substantial effect. The reason is that at the base level, emissions are related to physical activities in manufacturing, the service industries and in consumption. These activities are usually aggregated within a country by use of a monetary unit (other metrics could have been employed, for instance working man-hours), and a national or regional emission coefficient is calculated by comparing base year emissions with base year economic activity measures in monetary units. The economic activity is then projected into the future based on assumed or modelled development in the labour force, capital stock, productivity of the input factors, etc., as is the development of the emission coefficients. At the end of the simulation period, these entities are combined to produce emission levels measured in physical units. The choice of metric for the economic activity will clearly influence the numerical values also of the emission coefficients. However, if a consistent set of metrics is employed, it is difficult to see reasons why the choice of metric should affect the final emission level substantially.

Nevertheless, Manne and Richels (2003) and McKibben *et al.* (2004a,b) in their modelling work find some differences in emission levels between using PPP and MER based estimates, as a result of counteracting influences in their models. Detailed analysis of their work shows that these results critically depend on the combination of convergence assumptions, and not all relationships within the model seem to have been adjusted for the switch in metric. Holtsmark and Alfsen (Holtsmark and Alfsen, 2004a, b) showed that in their simple model consistent replacement of the metric for economic activities (PPP for MER) − for income levels as well as for underlying technology relationships − leads to a full cancellation of the impact of choice of metric on projected emission levels. While using PPP values might give rise to lower economic growth rates for developing countries under the convergence assumption – it will also have an impact on the relationship between income and demand for energy with lower economic growth leading to slower improvements in energy intensities. On the basis of these studies, it seems likely that using PPP-based values instead of MER-based values would at most only mildly change results in terms of physical parameters, such as energy use or greenhouse gas emissions measured in physical units.

3.2.1.3 Energy use

Future evolution of energy systems is a fundamental determinant of GHG emissions. With current technologies, high energy consumption leads to high emissions. However, what is more important for emissions is the structure of future energy systems. High carbon intensities of energy – namely high shares of fossil energy sources, especially coal, in total energy consumption – lead to scenarios with the highest CO_2 emissions (Nakicenovic *et al.*, 2000). Energy demand growth is ‘derived’ in most of the models. It depends on the main driving forces such as demography, structure and nature of human activities such as mobility, information processing and manufacturing. The following chapters (4 through 10) of this assessment report deals in detail with such sectoral developments. Chapter 11 summarizes the short to medium term options. Here we compare the range of energy requirements across new long-term energy scenarios.

Figure 3.6 compares the range of the 190 pre-SRES scenarios with 216 new, post-SRES, long-term energy scenarios in the literature. The ranges are comparable, with very small changes, namely that the extreme high end and low end of the distributions are not represented in the more recent energy scenarios. It is interesting to note that the median is now somewhat lower. In general, our conclusion is that the energy growth observed in the newer scenarios does not deviate significantly from previous ranges as reported in the SRES.

[INSERT **Figure 3.6** here]

3.2.1.4 Land use change and land use management

Land use is crucial in climate stabilization for its atmospheric inputs, which are shaped by market demands for land-based goods and services and regional climate and atmospheric feedbacks. Over the past several centuries, human intervention has markedly impacted land surface characteristics, in particular through large-scale land conversion for cultivation (Vitousek *et al.*, 1997). Land cover changes impact atmospheric composition and climate via two mechanisms: biogeophysical and biogeochemical. Biogeophysical mechanisms include the effects of changes in surface roughness, transpiration, and albedo that over the last millennium are thought to have had a global cooling effect (Brovkin *et al.*, 1999). Biogeochemical effects result from the large direct emissions of CO_2 into the atmosphere from deforestation. Cumulative emissions from historical land cover conversion for the period 1920–1992 have been estimated to be between 56.2 and 90.8 Pg C (McGuire *et al.*, 2001), and as much as 156 Pg C for the entire industrial period 1850–2000 (Houghton, 2003). In addition, land management activities that occur as part of each land-use/cover (e.g., cropland fertilizer and water management, manure management, and forest rotation lengths) also affect land-based GHG emissions.

Even if land activities are not considered as mitigation alternatives by policy, land’s dynamic atmospheric inputs role (emissions, sequestration, and albedo) is paramount, as is its susceptibility to changes in the atmospheric condition. Figure 3.7 portrays these relationships. Many recent studies have shown that land use (Gitz and Ciais, 2004) and feedbacks in the society-biosphere-atmosphere system (Strengers *et al.*, 2004) must be considered for realistic estimates of the future development of the carbon cycle. However, so far, future changes in land use are rarely addressed explicitly in carbon cycle studies. First approaches to study the effects of future land-use changes on the carbon cycle at the global scale employ trend extrapolations (Cramer *et al.*, 2004), extreme assumptions (House *et al.*, 2002), or derive trends of land-use change from the SRES story lines (Levy *et al.*, 2004).

[INSERT **Figure 3.7** here]

In Table 3.1 the most important land-use drivers are summarized. In general, the drivers influence either the demand for land-based products and services (e.g., food, timber, bio-energy crops, and ecosystem services) or land-use production possibilities and opportunity costs (e.g., yield improving technologies, temperature and precipitation changes, and CO_2 fertilization).

Food demand is a dominant land-use driver, and population growth and economic growth are the most significant food demand drivers through per capita consumption. Total world food consumption (kcal) is expected to increase by greater than 50 per cent in 2030 (Bruinsma, 2003). Moreover, economic growth is expected to generate significant structural change in consumption patterns, with diets shifting to include more livestock products and fewer staples such as roots and tubers. As a result, per capita meat consumption is expected to show a strong global increase, on the order of 25 per cent in 2030, with faster growth in developing and transitional countries of more than 40 per cent and 30per cent, respectively (Bruinsma, 2003; Cassman, 2003). The Millennium Ecosystem Assessment scenarios projected that global average meat consumption would increase from 36 kg/person in 1997 to 41 – 70 kg/person by 2050 , with corresponding increases in overall food and livestock feed demands (Millennium Ecosystem Assessment, 2005).

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[INSERT **Table 3.1** here]

Only a few global studies have focused on long-term (century) land use projections. The most comprehensive studies in terms of sector and land type coverage are SRES (Nakicenovic *et al.*, 2000), the SRES implementation with the IMAGE model (Strengers *et al.*, 2004), the scenarios from the Global Scenarios Group (Raskin *et al.*, 2002), UNEP's Global Environment Outlook (GEO3, 2002) and the Millennium Ecosystem Assessment (MA, 2005). Recent sector specific economic studies have also contributed global land-use projections for climate analysis, especially for forestry (Sands and Leimbach, 2003; Sohngen and Mendelsohn, 2003; Sohngen and Mendelsohn, forthcoming; Sathaye *et al.*, forthcoming; Sohngen and Sedjo, forthcoming). In general, in comparison to the SRES land-use projections, the, post-SRES scenarios have projected greater global cropland area, smaller forest land area, and mixed results for changes in global grassland and biomass crop acreage.

Most post-SRES global scenarios project significant changes in agricultural land caused primarily by changes in food demand and the structure of supply as moderated by international trade. Scenarios with a greater extent of agricultural acreage result from assumptions about higher population growth rates, higher food demands, and lower rates of technological improvement that generate negligible increases in crop yields. Combined, these effects are expected to lead to a sizable expansion (up to 40per cent) of agricultural land between 1995 and 2100. Conversely, lower population growth and food demand, and more rapid technological change, are expected to result in lower demand for agricultural land (as much as 20per cent less global agricultural acreage by the end of the century). In the near-term, all scenarios suggest an increase in agricultural acreage to meet projected increases in food demands over the next few decades. The global forest scenarios largely mirror the agricultural scenarios; thereby, illustrating both the positive and negative aspects of some existing scenarios modelling. Most of the long-term scenarios listed above assume that forest trends are driven almost exclusively by cropland expansion or contraction, and only deal superficially with driving forces such as global trade in forest products, conservation demands, and the establishment of future forest plantations to sequester carbon from the atmosphere. Global integrated assessment and computable general equilibrium scenario models in general are beginning to more directly and realistically model the competing driving forces of land use/cover change.

Without incentives or technological innovation, biomass crops are currently not projected to assume a large share of global land cover. However, a number of biomass energy potential assessments have been conducted at a global scale (see Berndes *et al.* (2003) for an overview). Except for the studies conducted by Fischer and Schrattenholzer (2001), Sorensen (1999) and Hoogwijk *et al.* (2005), most of the assessments are done with large regional spatial resolutions. Present studies as a whole are relatively weak in describing land competition with food supply and timber production (an exception is Sands and Leimbach, 2003), which has a significant influence on the economic potential of bio-energy crops. Hoogwijk *et al.* (2005) examined the potential of abandoned agricultural lands for providing biomass for primary energy demand, and found that this source is limited and other more costly lands would be needed if supplies of biomass were to keep up with projected total primary energy demand (e.g., in the SRES A2 scenario abandoned agricultural lands under the SRES A2 scenario could provide for only 20per cent of the total energy demand).

3.2.2 Emissions

The span of CO_2 emissions across baseline scenarios in the literature is still large, with 2100 emissions ranging from about today's levels to around 60 GtC. The possible interpretations of this large range of uncertainty about future emissions in scenarios are many. The most important is that the great uncertainty as to how the main driving forces, such as population growth, economic development, and energy production, conversion and end use, might unfold during the century as shown above.

3.2.2.1 CO_2 emissions from energy and industry

This category of emissions encompasses CO_2 emissions from burning fossil fuels, and industrial emissions from cements production and sometimes feedstocks[3]. Figure 3.8 compares the range of the pre-TAR baseline scenarios with the post-TAR baseline scenarios. The figure shows that the scenario range has remained almost the same since the TAR. There seems to have been an upward shift on the high end, but careful consideration of the data shows that this is caused by only 4 scenarios and the change is therefore not significant. The vast majority of scenarios, both pre- and post- TAR indicate an increase of emissions across most of the century, resulting in a range of 2100 emissions of 15 to 25 GtC. Also the range of emissions depicted by the SRES scenarios is consistent with the range of other emission scenarios reported in the literature; both in the short- and long-term (see Van Vuuren and O'Neill).

[INSERT **Figure 3.8** here]

Several reasons may contribute to the fact that emissions have not declined in spite of somewhat lower projections for population and GDP. An important one is that the lower demographic projections are only recently being integrated into emission scenario literature. Second, indirect impacts in the models are likely to offset part of the direct impacts. For instance, lower energy demand leads to lower fossil fuel depletion, thus allowing for a higher share of fossil fuels in the total energy mix over a longer period of time. Finally, in recent years there has been increasing attention to the interpretation of fossil reserves reported in literature. Some models may have decreased oil and gas use in this context, leading to higher coal use (and thus higher emissions).

Analysis of scenario literature using the so-called Kaya identity, shows that almost all baseline scenarios indicate a continuous decline of the primary energy intensity (E/GDP), while the change in the carbon factor (C/E) is much slower – or even stable (see Figure 3.9). In other words, in the absence of climate policy, structural change and energy efficiency improvement do contribute to

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[3] It should be noted, however, that there sometimes are large ambiguities on what is actually included in emissions scenarios reported in the literature. Some of the CO_2 emissions paths included in the ranges may therefore also include non-energy emissions such as those form land-use changes. However, since non-energy-related emissions are low compared to energy-related ones, their impact on the results of the scenario comparisons is nevertheless expected to be negligible.

lower emissions, but changes in the energy mix have a much smaller (or even zero) contribution. This conclusion is true for both the pre- and post-TAR scenario literature. One change seems to have happened, which is that the low range of carbon factor scenarios (thus those with a very rapid decline of this factor) is not present in the current literature.

[INSERT **Figure 3.9** here]

Comparing the different approaches to scenario development

Three baseline emissions projections generally come from 3 types of studies: 1) studies with one particular baseline, meant to represent a ‘best-guess’ of what might happen if present days trends continue, 2) studies with multiple baseline scenarios under different assumptions (storylines) and 3) studies based on a probabilistic approach. Below Figure 3.10 makes a tentative comparison of the outcomes of these approaches by comparing the outcome of baseline reported in the set of EMF-21 scenarios to the outcomes of the SRES scenarios. Category 1 is the different models in the EMF 21 study reporting their best-guess scenario; category 2 is the outcomes of SRES; and category 3 is the outcomes of two studies that have estimated probability ranges (see Webster *et al.*, 2002; Richels *et al.*, 2004 for the probability studies).

The figure shows that the overall uncertainty range of the first category is somewhat smaller than those of the second two categories, although the difference is rather small. In the first category, uncertainty mainly originates from different modelling approaches and from modeller’s insights into ‘the mostly likely values’ for driving forces. The third and especially the second category of scenarios explicitly assume more radical developments, but the number of studies involved is smaller. This leads to the low end of scenarios for the second category with very specific assumptions on development that may lead to low greenhouse gas emissions. The range of scenarios in the third category is somewhat in between these extremes. Overall, the three different approaches seem to lead to very consistent results, confirming the range of emissions reported in Figure 3.10 and confirming the emission range indicated by IPCC’s SRES scenarios.

In conclusion, when surveying the emission scenario literature since the last IPCC assessment (TAR), we find that the range reported there, by and large, still is representative of the available literature.

[INSERT **Figure 3.10** here]

3.2.2.2 Anthropogenic land emissions and sequestration

Some of the first global scenario analyses to account for land-use related emissions were the IS92 scenario set (Legett *et al.*, 1992) and the SRES scenarios (Nakicenovic *et al.*, 2000). However, out of the six SRES models, only three dealt specifically with land use (ASF: Lashof and Tirpak, 1990; IMAGE 2.1: Alcamo *et al.*, 1998; and AIM: Kainuma *et al.*, 2003), while only the latter two models included spatially explicit land-use models that simulated crop productivity patterns. Although, the SRES effort was a landmark in scenario development, the treatment of land-use emissions was poor in terms of the modelling of land-use drivers and the many emissions sources and GHGs. Also, the spatial resolution of the SRES land-use emissions was too coarse to provide adequate input to other studies. Some of these criticisms were addressed in the IMAGE 2.2 model implementation of the SRES scenarios (IMAGE team, 2001). The IMAGE 2.2 SRES implementation projected land emissions that ranged from 6 to 36 Pg CO_2-equivalent per year in 2100 for the B1 and A1FI scenarios respectively (Strengers *et al.*, 2004), with each scenario projecting different emissions pathways. The A2 scenario showed a continuous increase in emissions to a very high 35 Pg CO_2-equivalent per year. A1FI (with a large share of energy fossil fuel use) land emissions also monotonically increased but tended to stabilize at a somewhat lower level than A2. All other scenarios peaked after approximately 50 years then decreased to levels between 6 and 18 Pg CO_2-equivalent per year. This pattern is mainly due to a combination of rapid technological development and shifts to other energy sources. The B1 scenario produced the lowest emission levels at 70per cent of current levels (Strengers *et al.*, 2004). Other integrated assessment models are known to model land-use emissions; however, to date, they have not published baseline results.

Explicit global modelling of forests is important because of their role in the global carbon cycle. An estimated 1,146 Gt C are stored within the 4.17 billion hectares of tropical, temperate and boreal forest areas. A third of this carbon is stored in forest vegetation, and the rest in forest soils (Watson *et al.* 2000). Another 634 Gt C is stored in tropical savannas and temperate grasslands. Watson *et al.* (2000) estimate a net terrestrial carbon uptake of 0.7±1.0 Gt C/year. The amount of carbon sequestered through forestation in future scenarios depends critically on future baseline land use change scenarios. In addition, the major ecological processes of photosynthesis and respiration determine the terrestrial C cycle. Responsive to the climate/atmospheric feedbacks, these processes can have negative (slowing down) or positive (accelerating) effects on CO_2 fluxes and increases of atmospheric CO_2. The feedback effects on CO_2 concentrations can be substantial, particularly over the long-run. For example, a small difference of 0.2 Pg C per year in C fluxes could lead to a cumulative 10-ppmv difference in atmospheric concentrations over a century. At this point, the net influence of these feedback processes is uncertain (see WGII's discussion of food, fibre, and forest products).

Future projections of forest carbon sinks are usually performed on the basis of either different high-level driver scenarios (Nakicenovic *et al.*, 2000; MA, 2005), deforestation and afforestation assumptions extrapolated from trends (Sathaye *et al.*, in press), or assumptions on increases in forest products demand and the opportunity costs of non-forest land, as well as detailed accounting of forest composition and sequestered carbon (Sohngen and Sedjo, in press). Forest sequestration projections are usually reported as a net sum of deforestation emissions and additional carbon sequestration through afforestation. Like most of the SRES land-use change emissions scenarios, recent studies project global forests to be net emitters over most of the next century, with annual emissions declining over time with the slowing of tropical deforestation (van Vuuren *et al.*, forthcoming; Sohngen and Sedjo, forthcoming; Sathaye *et al.*, forthcoming). Recent estimates project baseline annual global net forest carbon emissions of approximately 0.3 to 0.6 GtC in 2050 and -0.6 to 0.2 GtC in 2100, well within the broad SRES ranges that result from the various SRES storylines. However, Leemans *et al.* (2002) showed that uncertainties in the carbon cycle can cause large variation in future CO_2 sequestration projections. They concluded that the potential differences in resulting CO_2 concentrations are large.

3.2.2.3 Non-CO_2 greenhouse gas emissions

The emissions scenario chapter in TAR (Morita et al, 2001) recommended that future research should include greenhouse gases (GHGs) other than CO_2 into new scenarios work. The reason was that at that time, certainly regarding mitigation, most of the scenarios literature was still primarily focused on CO_2 emissions. Nevertheless, some multigas scenario work existed, including the SRES baseline scenarios, but also some other modeling efforts (Manne and Richels 2000, Babiker et al 2001, Tol 1999). The most important other GHGs or non-CO_2 gases include: methane (CH_4), nitrous oxide (N_2O), and a group of fluorinated compounds (HFCs, PFCs, and SF_6). Since the TAR, the number of modeling groups producing long-term emission scenario of non-CO_2 gases has dramatically increased. As a result the quantity and quality of non-CO_2 emissions scenarios has improve appreciably.

Unlike CO_2 where the main emission-related sectors are few, i.e., energy, industry, and landuse, non-CO_2 emissions originate from a larger and more diverse set of economic sectors. See Table 3.2 for a list of major GHG emitting sectors and their corresponding emissions estimated for 2000. To make the non-CO_2 emissions comparable to those of CO_2, the common practice is to compare and aggregate emissions by using global warming potentials (GWPs).

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[INSERT **Table 3.2** here]

The most important work on non-CO_2 GHG emissions scenarios has been done in the context of EMF 21. The EMF 21 study updated the capability of long-term integrated assessment models for modeling non-CO_2 GHG emissions. The results of the study are illustrated in Figure 3.11.

[INSERT **Figure 3.11** here]

Evaluating the long-term projections of anthropogenic methane emissions from the EMF 21 data show a significant range in the estimates[4]. The differences in model results for methane emissions start with a range between 1.37 to 2.01 GtCe (average of 1.67 GtCe) for 2000, grow to a range between 1.87 to 3.82 GtCe (average of 2.84 GtCe) for 2050, and continue to a range between 1.59 to 4.67 GtCe (average of 3.19 GtCe) for 2100. For further evaluation, emissions from SRES are compared to the EMF 21 range and show that for methane emissions, the two data sets are fairly consistent. The ranges, however, are caused by different uncertainties. The methane emissions differences in SRES are due to the different storylines. The differences in the EMF 21 reference cases are do mainly to changes in the economic activity level projected in key sectors by each of the models. This could include, for example, increased agriculture production or increased supply of natural gas and below ground coal in the energy sector. In addition, different modeling groups employed various methods of representing methane emissions in their models and also made different assumptions as to how specific methane emission factors for each economic sector change over time. Finally, it should be noted that the degree to which agricultural activities are represented in the models differs largely. For example, some models represent all agricultural output as one large commodity, ‘agriculture,’ while others have considerable disaggregation. More disaggregated models can define emissions factors in more specific way. Interestingly, the latter group models tend to find slower emissions growth rates (see van Vuuren *et al.*, 2005).

The range of long-term projections of anthropogenic nitrous oxide emissions is wider for methane in the EMF 21 data. Here the differences in emission projections start with a range between 0.49 to 0.95 GtCe (average of 0.81 GtCe) for 2000, grow to a range between 0.51 to 1.83 GtCe (average of 1.22 GtCe) for 2050, and continues to a range between 0.56 to 3.14 GtCe (average of 1.22 GtCe) for 2100. Note that for N_2O, base year emissions of the different models differ substantially. Two factors may contribute to this. First of all, different definitions exist of what should be regarded as human-induced and natural emissions in the case of N_2O emissions from soils. Secondly, some models may not have included all emission sources. The same argument on the cause of future differences as mentioned under methane also applies here.

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[4] In the EMF21 study, reference case scenarios were considered to be ‘modelers choice’ where harmonization of input parameters and exogenous assumptions was not sought.

The last group of non-CO_2 gases are fluorinated compounds which including hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). The global total emissions of these gases are estimated at 122 MtCe or slightly over 1 per cent of all GHG for 2000. While the emissions of some fluorinated compounds are projected to decrease, many are expected to grow substantially because of rapid growth rate of some emitting industries (e.g., semiconductor manufacture and magnesium production and processing), and the replacement of ozone-depleting substances (ODSs) with HFCs. Long-term projections of these fluorinated GHGs are generated by a fewer number of models but still show a wide range in the results over the century. The range of emissions in 2000 is quite small. For 2050, this grows to a range between 0.44 to 0.79 GtCe (average of 0.57 GtCe), and widens to a range between 0.54 to 1.36 GtCe (average of 0.83 GtCe) for 2100. The range of the SRES results compared to the EMF 21 results is about the same.

Overall, it has to be concluded that since SRES the level of information on non-CO_2 emissions has increased substantially. The range of projections, however, is still more-or-less the same. This range indicates that the emissions of non-CO_2 GHGs as a group are projected to increase, but somewhat less rapidly as CO_2 emissions. The main reason is that the most important sources of CH_4 and NO_x are agricultural activities – which grow at a less rapid rate than energy use (the main source of CO_2 emissions).

3.2.2.4 Scenarios for Air Pollutants and Other Radiative Substances

3.2.2.4.1 Sulfur Dioxide Emissions Scenarios

Sulfur emissions are relevant for climate change modelling as they contribute to the formation of aerosols that, taken together, reduce radiative forcing. Sulfur emissions also contribute to regional and local air pollution. Historically, global sulfur dioxide emissions have been growing rapidly approximately in parallel with the increase in fossil fuel use (Smith *et al.*, 2001 and 2004; Stern, 2005). Since about the late 1970s, however, the growth in emissions has slowed down considerably (Gruebler, 2002). Implementation of emissions controls, a shift to lower sulfur fuels in most industrialized countries, and the economic transition process in Eastern Europe and the Former Soviet Union have contributed to the lowering of global sulfur emissions (Smith *et al.*, 2001). Conversely, with accelerated economic development, the growth of sulfur emissions in many parts of Asia has been fast in the recent decades, albeit growth rates have declined considerably recently (Streets *et al.*, 2000; Stern 2005; Cofala *et al.*, forthcoming; Smith *et al.*, 2004). A review of the recent literature indicates that there is considerable uncertainty concerning present sulfur emissions, showing a range for global anthropogenic emissions for the year 2000 between 55.2 MtS (Stern, 2005), 57.5 MtS (Cofala *et al.*, forthcoming) and 62 MtS (Smith *et al.*, 2004).[5]

Many empirical studies have explored the relationship between the above drivers of sulfur emissions and economic development (Gruebler, 1998, and Smith *et al.*, 2004). Driving factors are increasing income, changes in the energy mix, and a greater focus on air pollution abatement (as a consequence of increasing affluence). Together, these factors may result in inverted U-shaped pattern of SO_2 emissions. Emissions increase initially at early stages of industrialization, peak and then fall at higher levels of income, following environmental Kuznets curves (World Bank, 1992). This general trend is also apparent in most of the recent emissions scenarios in the literature.

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[5] Note that the Cofala *et al.* inventory does not include emissions from biomass burning, international shipping and aircrafts. In order to enhance comparability between the inventories, emissions from these sources have been added from xx to the original Cofala *et al.* values.

Over time, new scenarios have generally produced lower SO_2 emissions projection. The SRES scenarios, for instance, reported substantially lower sulphur emissions than the first set of IPCC scenarios. A comprehensive comparison of SRES and more recent sulfur emissions scenarios is given in Van Vuuren and O'Neill (forthcoming). Figure 3.12 illustrates the resulting[6] spread of sulfur emissions over the short term (up to the year 2050) is predominantly due to the varying assumptions for the timing of future emissions control, particularly in developing countries. Scenarios on the lower bound assume the rapid introduction of sulfur control technologies on global scale, and hence, a reversal of historical trends and declining emissions already in the initial years. Conversely, the upper bound of emissions are characterized by a rapid increase over the next decades, primarily driven by increasing use of coal and oil at relatively low levels of sulfur control (A1 and A2).

The comparison shows that overall, the older SRES scenarios are fairly consistent with recent projections concerning the lower bound estimates as well as regarding the long-term uncertainty range, 11 to 93 MtS in SRES compared to 11 to 103 MtS for the year 2100, (Smith *et al.*, 2004; see Figure 3.12). However, the emissions peak over the short term of some high emissions scenarios in SRES lie above the upper bound estimates of the recent scenarios. There are two main reasons for this difference. First, recent sulfur inventories for the year 2000 have shifted downwards (for a discussion see further above in this Section). Secondly, and perhaps more importantly, new information on present and planned sulfur legislation in some developing countries, such as India (Charmichael *et al.*, 2002) and China (Streets *et al.*, 2001) has become available. Anticipating this change in legislation, recent scenarios project sulfur emissions to peak earlier and at lower levels as compared to SRES.

[INSERT **Figure 3.12** here]

3.2.2.4.2 NO_x Emissions Scenarios

The most important source of NO_x emissions are fossil fuel combustion and industrial processes, 23.4 MtN per year in 1990, although other important sources constitute natural and anthropogenic soil release, biomass burning, lightning, and atmospheric processes, which together amount to around 25 MtN per year. Considerably uncertainties exist particularly around the natural sources (Prather *et al.*, 1995; Olivier *et al.*, 1998, Olivier and Berdowski, 2001, Cofala *et al.* (forthcoming). Fossil fuel combustion in the electric power and transport sectors is the largest source of NO_x. In recent years, emissions from fossil fuel use in North America and Europe are either constant or declining. In most parts of Asia, however, emissions are believed to increase considerably (van Aardenne, 1999; Cofala *et al.*, forthcoming). An important reason is that it is difficult to abate NO_x emissions in the growing transport sector. It should be noted that, whereas SO_2 emissions relate closely to the type of fuel, NO_x emissions are more dependent on the combustion technology and conditions.

Few scenarios for NO_x emissions exist beyond the studies for Europe, North America, and Asia (the earlier IS92 scenarios and SRES are a notable exception). Some scenarios, such as those by Bouwman and van Vuuren (1999) and Collins *et al.* (1999) often still use IS92a as a 'loose' baseline, with new abatement policies added as they were introduced in the OECD countries after 1992. More recent scenarios include the Cofala *et al.* (forthcoming) projections up to 2030, which are based on a comprehensive assessment of present (and planned) national legislation for NO_x control. Their 'current legislation' scenario projects emissions to stay at about present levels for the next

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[6] The Amann (2002) projections were replaced by the recently updated IIASA-RAINS projection from Cofala *et al.* (2005) forthcoming

two decades and to increase slightly thereafter between 2020 and 2030. Cofala *et al.* (forthcoming) also explore a hypothetical maximum feasible reduction scenario, in which global NO_x emissions decrease by 75 per cent in 2030. Up to the 2020s, all scenarios project rising NO_x emissions (Figure 3.13). Another new scenario was developed by Smith *et al.*, (2004) using an updated version of the MiniCAM model with revised parameterization for NO_x control. In the short-term the Smith *et al.* scenarios range between 32 and 47 MtN by 2020, which corresponds to an increase in emissions of about zero to 50 per cent compared to 2000. The long-term spread is considerably larger, ranging from 9 to 74 MtN by 2100 (see Figure 3.13). A comparison of global NO_x emissions in the four SRES marker scenarios and the development of the 5th, median, and 95th percentile of the distribution of all 40 SRES scenarios with the Smith *et al.* and Cofala *et al.* projections is given in Figure 3.13. It is apparent from the illustration that recent projections have shifted downwards compared to SRES, particularly in the short term.

[INSERT **Figure 3.13** here]

3.2.2.4.3 Emissions Scenarios for Black and Organic Carbon

Black and Organic Carbon Emissions (BC and OC) are mainly formed by incomplete combustion of fossil fuels and biomass as well as from gaseous precursors through nucleation and condensation processes (Penner *et al.*, 1993; Gray & Cass 1998). Although often treated as separate components, the elemental and organic fractions are rarely found as separate individual particles, but rather forming complex mixtures together and with other aerosol species (Ogren 1982). The main anthropogenic sources of BC and OC emissions include fossil-fuel combustion in industry, power generation, traffic and residential sectors as well as biomass and agriculture waste burning. Also the use of traditional fuels and poor combustion technologies, especially in developing countries results in significant BC and OC emissions. The magnitude of emissions largely depends on the efficiency of the combustion practice as well as the type of fuel used. Natural sources like forest fires and savannah burning are other major contributors.

BC and OC particles have been linked with adverse health effects. In addition, airborne black carbon absorbs solar radiation and thus contributes to the warming of the climate (Hansen *et al.* 2000; Andrae 2001; Jacobson 2001). The global mean radiative forcing of black carbon aerosols from fossil fuels has been estimated by IPCC at +0.2 Wm-2 with an uncertainty range from +0.1 to +0.4 Wm-2 (Ramaswamy *et al.*, 2001). The uncertainty of these estimates is high (see also Jacobson (2001) and Penner *et al.* (2003)).

At the moment, emission and concentration data on BC and OC is relatively poor and there role is also poorly represented in climate models. In IPCC's Third Assessment Report presented long-term projections of BC and OC that were developed by scaling present-day emission estimates using projections of CO emissions (IPCC, 2001). Recently, a handful of detailed global emission inventories of BC and OC have become available (e.g. Cooke *et al.*, 1999; Bond *et al.*, 2004). This has resulted in the possibility of developing new global estimates of long-term BC and OC emissions. However, still considerable uncertainty exists (Table 3.3). Most of the uncertainties result due to two main factors: the variety in combustion techniques for different combustors as well as the method of measurement of emissions. In order to represent the uncertainties in emission inventories, some of the studies like Bond *et al.* (2004) provide ranges of emissions with estimates of high, low and 'best-guess' values. In addition to these global numbers, also regional estimates have been made.

[INSERT **Table 3.3** here]

Projection of global BC and OC emissions into the future is a difficult task. Emissions are largely region specific and depend on local combustion practices and fuels, and are not easy to estimate. New scenarios have been made by Streets *et al.* (2004), Rao *et al.* (2005) and Louisse *et al.* (2005). Streets *et al.* (2004) use a detailed technology bottom-up approach to develop BC and OC emission pathways for all the SRES scenarios until 2050. They use the scenarios, fuel use projections and assumptions on technological change in the scenarios exogenously to calculate the resulting emissions from both contained combustion from fossil fuels and biomass as well as natural sources. Rao *et al.* (2005) use a bottom-up energy model to examine the BC and OC emissions from contained combustion of fossil fuels and biomass for two IPCC scenarios: B1& A2. In their scenario affluence leads to an additional premium on local air quality. Liousse *et al.* (2005) use the fuel-use information from the IPCC SRES scenarios but apply static emission factors exogenously to this mix to obtain corresponding BC and OC emissions from both contained combustion and natural sources.

While the above mentioned scenarios have similar assumptions on population and economic drivers, there is considerable divergence in the results, as seen in Figure 3.14. Partly, the difference is due to the base year estimates. Another important difference in these scenarios is the inclusion of technological change. Liousse *et al.* neglects the effects of technological change leading to much higher emission estimates as compared to Streets *et al.* (2004) and Rao *et al.* (2005). In addition, Rao *et al.* (2005), also account for various short-term local pollutant policies that have synergies for BC and OC emissions and that may further explain some of the differences. These differences highlight the importance of a comprehensive framework for long-term pollutant emissions estimations that captures the complex dynamics of structural and technological change in the energy system.

[INSERT **Figure 3.14** here]

When comparing the development in combustion related BC and OC emissions across regions and sectors, some similar trends are observed in the different studies. Developing countries dominate in BC and OC emissions by the end of the century in spite of considerable reductions in emissions due to technological advancements and fuel-shifts. Both Streets et al (2004) and Rao *et al.* (2005) show a general decline in BC and OC emissions in developed countries as well as regions like East Asia (including China). Other developing regions like Africa and South Asia are assumed to exhibit much slower technology penetration rates with emissions largely staying constant or even slightly increasing by the end of the century. There is a large decline in emissions from the residential sector, especially in the developing countries, because of the gradual replacement of traditional fuels and technologies with more efficient ones. Transport related emissions in industrialized countries, decline continuously due to stringent regulations, technology improvement and switches to cleaner fuels like alcohols and hydrogen. Both studies estimate that in the longer term, there are overall declines in BC and OC emissions from the transport sector in most developing countries, albeit at a slower rate than developed countries. In the future, it is possible that specific policies targeting BC and OC emissions may come about as a result of growing concerns about their health impacts, but global greenhouse gas climate policies may also offer significant co-benefits for many air pollutants including BC and OC aerosols. In their study, Rao *et al.* (2005) find that climate policies that are directed at greenhouse gases can have significant co-benefits for local pollutants like BC and OC emissions, by providing the necessary impetus for adoption of cleaner fuels and advanced technologies.

While significant progress has been made in developing inventories of BC and OC emissions, there are still large uncertainties in the data due to lack of standardized approaches to measurement and resolving these uncertainties is vitally important. Climatic impact of carbonaceous aerosols is highly linked to their spatial distribution and it is thus necessary to obtain more detailed regional estimates of emissions. In addition, the long-term emission trajectories differ significantly across some of the studies and there needs to be consensus on the important drivers of aerosol emissions. Further, the exact climatic effects of BC and OC aerosols remain unclear and unless a complete understanding of this issue is reached by climate scientists, the efficacy of such emissions projections in formulating reliable policy recommendations remains uncertain.

3.2.3 Conclusions

The review of the recent literature on baseline emission scenarios and their driving forces published since 2001 indicate the following main findings:

- **Overall, the range of emissions reported before and after 2001 in scenarios without climate policy seems not to have changed.** Global CO_2 emissions in baseline scenarios range from 5 to about 60 GtC by 2100. The majority of scenarios projects emissions between 15 to 25 GtC. The SRES scenarios lie well within this range, although the B1 scenario describes an emission trend in far lower end.
- **Since 2000, new insights in likely demographic developments show lower projected population ranges than before 2001.** These new population projections are only now reaching emission scenario literature. All else being equal, lower population scenarios are expected to lead to lower emissions. However, indirect impacts such as the impact on depletion rates of fossil fuels (slower) or the coupling of low fertility levels to higher income levels might at least partly offset this impact.
- **There seems to be no major change in the literature for other driving forces since 2001.** The range of economic growth rates are somewhat narrower in the new literature, with differences being relatively minor compared to SRES. On the regional level, the very rapid growth rates in some developing regions of the SRES A1 scenarios lie above the recent estimates, particularly for the short term. It is not clear whether new interpretations of data on fossil fuel reserves or energy security consideration may have contributed to the constant emissions range (offsetting the impact of new demographic insights). Land use scenarios are still relatively scarce.
- **There is an emerging debate in scientific literature on the use of ppp-based income measures in the development of economic scenarios and the impact of this on emission scenarios. A number of studies conclude that the choice of economic metric (PPP or MER) might have just small implications for emissions projections .** In particular, the impact on economic modeling is unclear, with both advocates of new PPP-based modeling attempts and those who argue for continuing use of MER-based models. With respect to impacts on emissions, most researchers seem to agree that if PPP-based modeling leads to new perspectives on regional growth rates that should lead to changes in model parameterization of relationships between economic growth and physical activities. Changes in the latter are likely to offset changes in economic outlooks. There are several research questions on the use of PPP-based income metrics that need further research.
- **Sulfur and NO_x emission scenarios have come down since 2000**. New information on present and planned sulfur legislation in a number of developing countries, such as India and China, has become available since SRES. Anticipating this change in legislation, recent scenarios project sulfur emissions to peak earlier and at lower levels as compared to SRES. NO_x emissions scenarios in SRES underestimate future efforts for NO_x control. A revision of those scenarios using alternative models and improved parameterization for NO_x legislation is recommended.
- **A small number of new scenario studies have begun to explore emissions pathways for black and organic carbon.** Uncertainty in base year emissions and future technology development both contribute to a very wide range of projections.

3.3 Mitigation scenarios

3.3.1 Definition of a stabilization target

In response to the UNFCCC call for a 'stabilization of greenhouse gas concentrations at a level that prevents dangerous anthropogenic interference,' most mitigation studies have focused their efforts on generating stabilization scenarios. What to stabilize is a crucial issue. Some studies stabilize atmospheric GHG concentrations - CO_2 or multigas, which account for the different radiative properties and atmospheric lifetimes.

In general, selecting such a stabilization target early in the cause-effect chain of human activities to climate change impacts, such as emissions stabilization, increases the certainty of achieving required reduction measures, while increasing the uncertainty on climate change impacts (see Figure 3.15 and Table 3.4). Selecting a climate target further down the cause-effect chain (e.g. temperature change, or even avoided climate impacts) increases certainty on impacts, but decreases certainty on required reduction measures (UNFCCC 2002). Regardless of the target, the largest uncertainty is in the step from radiative forcing to temperature change and vice versa due to the large uncertainties in climate sensitivity (Matthews and van Ypersele 2003). An alternative is to formulate a GHG concentration target in terms of radiative forcing, thereby weighting the concentrations of the different gases by their radiative properties. The advantage of radiative forcing targets over temperature targets is that the calculation of radiative forcing does not depend on climate sensitivity. The disadvantage is that a wide range of temperature impacts are possible for each radiative forcing level. Temperature targets, on the other hand, have the important advantage of being more directly linked to climate change impacts.

Another approach is to calculate risks or probability of exceeding particular values of global annual mean temperature rise since pre-industrial times (ΔT) looking across various stabilisation or radiative forcing targets. For example, den Elzen and Meinhausen (2005) used two probability density functions of climate sensitivity (Wigley & Raper 2001, Murphy et al 2004) in the MAGICC climate model (IPCC 1997) to estimate that a 550 ppmv CO_2 equivalent stabilisation level has a risk of 75per cent of overshooting a limit of 2^oC ΔT, a 33per cent risk of overshooting 3^oC ΔT and 10per cent of overshooting 4^oC ΔT. Similarly Hare and Meinshausen (2005) draw on a wider range of probability distributions for climate sensitivity and emission scenarios as found in the literature to estimate the risk of overshooting various long-term stabilisation objectives; they estimate 68per cent-99per cent (with a mean of 85per cent) risk of overshooting 2^oC ΔT with stabilisation at 550 ppmv CO_2 equivalent.

[INSERT **Figure 3.15** here]

[INSERT **Table 3.4** here]

Table 3.4 could be used in selection of different targets for model comparison. However, in policy-making, generally a set of targets will be chosen, instead of a single target, that will be updated over time. For instance, a country may choose to set a temperature target of a maximum of 2 degrees Celsius temperature increase. In order to operationalize the target, the target is likely to be translated into maximum emission levels in particular years.

The choice of different targets is relevant because it leads to different uncertainty ranges and to different strategies and outcomes. Also, stabilization of one target does not imply stabilization of other targets. For example, Schaeffer *et al.* (2005) have shown that the most cost-effective way to stabilize temperature does not include stabilization of radiative forcing, but scenarios with radiative forcing peaking at a certain concentration, and then decreasing with rapid additional emissions reductions so as to avoid (delayed) further warming.

This chapter concentrates on comparing abatement actions to radiative forcing and GHG concentration stabilization targets. However, we will also discuss temperature stabilization targets.

3.3.2 How to define substitution among gasses

A method is needed to compare different greenhouse gases with different atmospheric lifetimes and different radiative properties. Ideally, the method would allow for substitution between gases (in order to achieve cost reductions) but ensures equivalence in climate impact. Fuglestvedt at al. (2003) provide a comprehensive overview of the different methods that have been proposed, and the advantages and disadvantages of using them. One of these methods, CO_2-equivalent emissions based on Global Warming Potentials (GW_p), has been adopted by current climate policies, such as the Kyoto Protocol and the United States climate policy (White-House 2002). Despite the continuing scientific debate on the use of GWPs - in particular they do not account for the economic dimension of the problem and are based on an arbitrary time horizon - the concept is regarded as convenient and, to date, no alternative measure has attained comparable status.

Other methods have been analyzed. In fact, models that intertemporally optimize can avoid the use of GWPs. Manne and Richels (2001) showed that GWPs as the basis of substitution did not lead to the cost-optimal path for the long-term targets they analyzed. In particular, reducing methane early had no climate benefit given its short life-time. The recent EMF-21 study validated this result. Figure 3.16 shows the projected EMF-21 CO_2, CH4, N2O, and F-gas reductions across models stabilizing radiative forcing at 4.5 W/m^2. Most of the EMF-21 models based substitution between gases on GWPs. However, three models substituted based on intertemporal optimization. Results from this latter group are indicated in red in Figure 3.16. While for most of the gasses, there are no systematic differences between the results from the two groups, for methane, there are clear differences. For models using GWPs (blue), the reduction of CH_4 emissions in the first three decades is substantial. The models that do not use GWPs (red), do not substantially reduce CH_4 until the end of the time horizon. Despite methane's short life-time, GWPs make CH_4 reductions appear to be a cost-effective near-term abatement strategy.

[INSERT **Figure 3.16** here]

While GWPs are not likely to lead to cost-effective stabilization solutions, they are practical. An exchange metric is needed to facilitate emissions trading between gasses. Having a metric broadens the set of abatement alternatives, creating potential savings opportunities through 'what flexibility' in emission trading schemes. Therefore, appropriate questions are what are the costs of using GWPs versus not using them; and, do other 'real world' metrics exist that could perform better? O'Neill (2003) and Person *et al.* (2004) have argued that the disadvantages of GWPs are likely to be outweighed by the advantages. This can be done by showing that the cost difference between a multi-gas strategy and a CO_2-only strategy is much larger than the difference between a GW_p-based multi-gas strategy and a cost-optimal strategy. Furthermore, the GW_p based strategy results in significantly less warming throughout its scenario period. GWPs have the advantage of not focusing on one particular target (here a long-term stabilization target), that in this case leads to considerable reductions of CH_4 early in the scenario period. Postponing the early CH4 reductions of the GW_p-based strategy (as is suggested by intertemporal optimization), leads to much greater increases of temperature in the 2000-2020 period as changes in the energy sector lead to reductions in sulfur cooling.

3.3.3 Scenarios

3.3.3.1 Energy and Industry CO_2

There are more than 700 emission scenarios in the literature including almost 400 baseline (non-intervention) scenarios and more than 300 mitigation (intervention) scenarios that assume policies to mitigate climate change. Many of these scenarios were collected during the IPCC SRES and TAR processes (Morita & Lee, 1998a) and made available through the Internet (Morita & Lee, 1998b). Systematic reviews of the baseline and mitigation scenarios were reported in the SRES (Nakicenovic *et al.*, 2000) and TAR (Morita et al, 2001) respectively. The corresponding databases have been updated and extended recently for the emissions scenario evaluation in AR4 (Kainuma *et al.*, 2005; Nakicenovic *et al.*, 2005). This section compares the recent mitigation scenario literature with the TAR mitigation scenarios.

The focus is on mitigation scenarios of global emissions over the next century. There are 354 mitigation scenarios that satisfy these criteria, 156 of which were developed after the TAR. Short-term scenarios with a regional or national focus are discussed in Section 3.3.5.

The CO_2 emissions projections for the 156 newer mitigation scenarios are summarized in Figure 3.17. Also shown, for comparison, are the 58 corresponding baseline scenarios. An initial observation is that the distribution of the mitigation scenarios in 2100 is primarily situated below the median of the baseline scenario distribution. In other words, mitigation measures and policies abate the upper half of the 2001 baseline distribution. Mitigation consequently reduces about half of the uncertainty about the range of future CO_2 emissions. The remaining emissions tend to be less closely tied to the baseline emissions drivers. Scenarios with low populations tend to be associated with higher rates of economic development and generally lower emissions per capita than scenarios with higher population that are usually associated with comparatively lower rates of economic development. However, higher rates of development translate into higher investments and higher human capacities that, in a mitigation scenario, translate into higher rates of adoption of more advanced and ‘cleaner’ technologies.

[INSERT **Figure 3.17** here]

The mitigation scenarios in the new literature can be classified into two types: scenarios that aim at stabilization of climate change (with respect to atmospheric concentrations, radiative forcing, or temperature change), and other mitigation scenarios that generally explore the implications of climate mitigation and policies, but without the ultimate goal of climate stabilization.

Examples of non-stabilization mitigation scenarios include analyses of the effectiveness of alternative mitigation policies and/or mitigation measures, detailed sectoral assessments and cross-sectoral cost comparisons, and estimation of the mitigation potential of specific technology options or clusters of technologies. For example, Riley *et al.* (2005) compare the effectiveness of two GHG abatement regimes: a global regime of non-CO_2 gas abatement, and a regime that is globally less comprehensive and mimics the present ratification of the Kyoto Protocol. The study concludes that a mitigation regime, which is globally comprehensive but has limited coverage of gases (non-CO_2 only), might be more effective in limiting temperature change and less expensive than the present configuration of Kyoto. In another example, Riahi *et al.* (2005) assess the potential of carbon capture and storage (CCS) in the power sector as a long-term mitigation option, concluding that although there is significant potential for CCS in the power sector, CCS alone won't be sufficient to stabilize atmospheric concentrations in the long term. As suggested by others, a portfolio of emissions reduction options is needed (Edmonds *et al.*, 2004; Pacala and Soclow, 2004).

Figure 3.18 portrays the projected CO_2 emissions associated with the new stabilization and non-stabilization mitigation scenarios. In addition, the figure depicts the range of the TAR stabilization scenarios (Morita *et al.*, 2001), comprised of more than 80 scenarios that are stabilizing atmospheric CO_2 between 450 and 750 ppmv. The median of the stabilization scenarios is lower than the median of the other mitigation scenarios, where the emissions profiles of most of the stabilization scenarios peak around the middle of the century, decline thereafter, eventually fall to well below current levels, and asymptotically cease altogether.

[INSERT **Figure 3.18** here]

An important characteristic of the new stabilization scenarios (green lines in Figure 3.18) is that they extend beyond the lower boundary of the range of TAR stabilization scenarios. An increasing body of literature is assessing the attainability of very low targets of 350 ppmv CO_2 and below (e.g., Azar *et al.*, 2005; van Vuuren, forthcoming, Riahi *et al.*, 2006). The attainability of such low targets is seen to depend on the technology 'readiness' of new and advanced technologies, such as carbon capture and storage in combination with fossil fuels and biomass energy conversion processes. If biomass is grown sustainably, the use of CCS in combination with biomass may lead to negative emissions (Williams, 1998; Obersteiner *et al.*, 2001 and 2002). Recent representations of these new technologies in integrated assessment models (e.g., MESSAGE, GET, Timer) has changed perceptions regarding the attainability of very low targets and expected costs. For example, Rao and Riahi (2005) illustrate the sensitivity of stabilization costs to the availability of negative emissions technologies, while Azar *et al.* (2005 and xx) find that while negative emissions technologies might be essential for achieving very stringent targets (350 ppmv and below), their importance diminishes at higher stabilization levels (>450 ppmv CO_2).

Another focus of the new literature of stabilization scenarios is multiple GHGs mitigation that accounts for feedbacks between sectors and drivers of CO_2 and non-CO_2 GHGs. Earlier studies had focused primarily on the stabilization of atmospheric CO_2 (TAR, 2001). A comprehensive international modeling comparison project on multiple gas stabilization was conducted by the 21st session of the Stanford-based Energy Modeling Forum (EMF-21: Weyant and de la Chesnaye, 2005). The study compares multigas 4.5 W/m^2 radiative forcing stabilization over the next century results from models that represent a wide range of alternative baseline scenarios.

The remainder of this sub-section discusses the implications of alternative stabilization targets, especially multigas targets, for CO_2 emissions, comparing the EMF21 scenarios to the TAR stabilization scenarios. A number of figures are used in this discussion. As a first order representation of the stringency of the alternative stabilization levels, the cumulative 2000-2100 CO_2 emissions of the scenario sets are portrayed in Figure 3.19. Alternative stabilization levels and metrics also have implications for the timing of emissions reductions. So, the relationship between alternative stabilization targets and the time at which emissions peak in reaching respective targets is shown in Figure 3.20. Finally, the necessary CO_2 emissions reductions and the relative marginal abatement costs of multigas mitigation are illustrated in Figures 3.21 and 3.22 respectively.

[INSERT **Figure 3.19** here]

[INSERT **Figure 3.20** here]
[INSERT **Figure 3.21** here]
[INSERT **Figure 3.22** here]

The development path of CO_2 emissions in the stabilization scenarios, i.e., when CO_2 emissions will have to peak, and how much cumulative emissions may be released to the atmosphere over the course of the century is subject to large uncertainties (Figure 3.19 and 3.20). Generally, more stringent stabilization levels permit less cumulative emissions over the course of the century, and the peak of CO_2 emissions occurs at earlier points in time. For example, the median cumulative CO_2 emissions in the TAR stabilization scenarios (Figure 3.19) rise from 600 GtC to about 1100 GtC if moving from a target from 450 to 650 ppmv. The uncertainties associated with individual TAR stabilization levels (shown by the error bars) are primarily due to alternative model parameterization of the carbon cycle and differences in emissions pathways. The uncertainty range is smaller at more stringent targets (450 ppmv), indicating the reduced flexibility of the emissions path and the requirement of early mitigation, e.g., 85per cent of the 450 ppmv TAR scenarios peak by 2030, compared to 2050 for the 650 ppmv TAR scenarios (Figure 3.20).

Comparing the new multigas mitigation scenarios to the TAR scenarios shows that a 4.5 W/m^2 constraint would require the stabilization of CO_2 concentrations at approximately 500 to 650 ppmv. A small number of outliers extend the post-TAR range below the 450 ppmv TAR range. Figure 3.19 shows also that a mitigation regime focused on CO_2 only would require more stringent median CO_2 emissions cut-backs of about 100 GtC over the course of the century to achieve the same 4.5 W/m^2 target. Multigas mitigation also has implications for the timing of CO_2 reductions. The peak of CO_2 emissions can occur decades later under a fully flexible multigas mitigation strategy (Figure 3.20).

The implications for emissions reductions in achieving the respective stabilization targets is summarized in Figure 3.21. The upper and lower panels illustrate the cumulative CO_2 emissions reductions by 2030 and 2100 respectively. The cumulative CO_2 reductions scenarios span large ranges for individual stabilization targets, even more so in the long term. The large uncertainty are not only due to alternative modeling methodologies and parameterizations, but also due to uncertainty of carbon emissions in the baseline. Higher emissions reductions are required for stabilization from more carbon-intensive baselines.

The median of the TAR stabilization scenarios (Figure 3.21) suggest an increase in required emissions reductions from 15 GtC to 50 GtC over the next three decades if the target is tightened from 650 to 450 ppmv CO_2, and from 400 GtC to more than 1600 GtC over the century. These central values are, as shown, surrounded by significant uncertainty.

Due to differences in the multigas and TAR scenario baselines, emissions reduction comparisons are limited. However, the same models were used for most of the newer CO_2/mulitgas stabilization comparisons. The majority of the multigas scenarios suggest cumulative emissions reductions between a few GtC to about 40 GtC by 2030. For achieving the same long-term target, the reduction effort by 2030 increases by about 50 per cent for CO_2 only mitigation (ranging between 7 GtC to 53 GtC by 2030). The same central tendencies of increasing reduction requirements in the CO_2-only scenarios are still visible in panel b of Figure 3.21 in the long-run. The multigas mitigation regime provides additional flexibility for direct management of non-CO_2 sources (Riley *et al.*, 2005; Smith *et al.*, 2005; van Vuuren *et al.*, 2005; Rao and Riahi 2005).

3.3.3.2 Non-CO_2 GHG

Since about 1999, more and more attention has been paid to incorporating non-CO_2 gases into climate mitigation and stabilization analyses. As a results, there is now a body of literature (see de la Chesnaye et al 2005, van Vuuren et al 2005, Weyant and de la Chesnaye 2005) showing that (1) there are greater and more diverse emitting sectors for non-CO_2 GHG than for CO_2; and (2) mitigation costs for these sectors can be lower than for energy-related CO_2 sectors. These two factors, taken together, lead to a larger portfolio of mitigation options for an economy. When all these options are employed in a multigas mitigation policy, there is a significant potential for reduced costs, for a given climate policy objective, versus the same policy when CO_2 is the only GHG directly mitigated. This multigas costs savings can be especially important where carbon dioxide is not the dominant gas, on a per centage basis, for a particular economic sector and even for a particular region.

For non-CO_2 these gases, a number of parallel numerical experiments have been carried out by the Energy Modeling Forum (EMF-21, Weyant and de la Chesnaye 2005). Even though it can be argued that abatement cost curves for these gases used in these experiments still rely on a few preliminary studies, the conclusion that acting on these gazes present the potential of cutting very significantly costs of meeting various emissions reduction targets at various points in time is robust. The most critical questions, from a policy point of view, are related to how to compare the relative contribution of these gases to climate forcing. They are indeed characterized by very different residence times in the atmosphere. Criticisms against the GWPs are well-established but there is currently no consensus about alternatives that can be easily used in optimal control models to study when it would be optimal to abate these gases. This technical difficulty explains why no study has been published so far in a stochastic optimal control framework in a way similar to studies on CO_2 or, here below, on biological carbon sequestration. Theoretical analysis suggests however two important conclusions: (1) if the pace of warming in further decades is viewed as a binding constraint (in a cost-efficiency framework) or as causing significant damages in the following decades, then abating short-lived gases such as CH_4, over the short run, would have a high social value; it would slowdown global warming and gain some time for displaying low cost carbon saving technologies; and (2) if global warming in further decades is viewed as less critical than possible high climate risks beyond given, currently unknown, concentration thresholds, then it would be economically more efficient to trigger abatements of short lived gases only after the resolution of information about these risks in order to facilitate the switching towards very tight concentration constraints.

Further research is needed and may be completed before the completion of the AR4, to scrutinize more in depth this trade-off, considering that all these gases are emitted by sectors very heterogeneous in terms of economics dynamics and technical inertias.

Given the recent work by the economic community to incorporate non-CO_2 gases into analysis of potential GHG mitigation and associated costs, this section looks at the recent EMF – 21 study for assessment of non-CO_2 mitigation. This was done by setting the modeling target of stabilizing radiative forcing at 4.5 W/m^2 compared to pre-industrial levels. Therefore, greenhouse gas emissions in the different models need to be reduced substantially in comparison to each model reference emission scenario. There were two cases or strategy employed to achieve the mitigation target: (1) directly mitigate CO_2 emissions from the energy sector (with some indirect reduction in non-CO_2 gases); and (2) mitigate all available GHG in a costs effective approaches using full 'what' flexibility.

In the CO_2-only mitigation cases the most significant mitigation is from CO_2 emissions which are reduced by about 75per cent in 2100 compared to baseline. At the same time, there are some emission reductions in CH_4 and N_2O as systemic changes in the energy system, induced by putting a price on carbon, also reduces these emissions. Emissions of CH_4 are reduced by about 20per cent and N_2O by about 10 per cent. These changes are illustrated in Figure 3.23.

[INSERT **Figure 3.23** here]

In the second multigas mitigation scenario, an appreciable per centage of the emission reductions occur through reductions of non-CO_2 gases, which then results in smaller required reductions of CO_2. The emission reduction for CO_2 in 2100 drops (on average) as a result from 75per cent to 67per cent. This per centage is still rather high, caused by the large share of CO_2 in total emissions (on average, 60per cent in 2100) and partly due to exhaustion of reduction options for the of non-CO_2 gases. The reductions of CH_4 across the different models averages around 50per cent, with remaining emissions coming from sources for which no reduction options were identified, such as CH_4 emissions from enteric fermentation. For N_2O, the increased reduction in the multi-gas strategy is not as large as for CH_4 (almost 40per cent). The main reason is that the identified potential for emission reductions for the main sources of N_2O emissions, fertilizer use and animal manure, is still limited. Finally, for the fluorinated gases, high reduction rates (about 75per cent) are found across the different models.

It should be noted that although the contributions of different gases change sharply over time, there is considerable spread among the different models. This also can be seen in Figure 3.23. Many models project relatively early reductions of both CH_4 and Fluorinated gases under the multi-gas case. However, the subset of models that does not use GWPs as substitution metric for the relative contributions of the different gases to the overall target, but does assume inter-temporal optimization in minimizing abatement costs , does not start to reduce CH_4 emissions substantially until the end of the period. The reason for this result is that in aiming at the long-term target, it does not pay to engage in early CH_4 emission reductions because CH4 has a short atmospheric life-time (about ten years). In other words, since the benefits to reducing a radiative forcing in the atmosphere are more immediately felt with CH_4 mitigation, these models ‘wait’ to reduce these emissions as the target approaches. In their calculations, there is not much benefit in reducing CH4 early in the simulation.

3.3.3.3 Costs and economic implications welfare losses, system costs, carbon values

This sections evaluates the post-TAR mitigation scenarios with respect to their corresponding reference scenarios. It is important to note that costs reported in this section do not take into account any co-benefits or the benefits of avoided climate-change related damages.

Evaluation of all the available scenarios shows that GDP loss may or may not be related to the GDP growth assumptions in baselines. For instance, high baseline economic growth would lead to higher emissions of GHGs, which would lead to increased GHG reduction costs compared to the corresponding mitigation scenario for a low-growth baseline. On the other hand, high economic growth could provide increased funds for research and development (R&D) of advanced technologies, which would decrease the cost of GHG reduction. The net cost would depend on the relative strengths of these effects. Another aspect is that the costs are also dependent upon the structure of economies, i.e., economies with high fossil fuel dependence, via either exports or domestic consumption, are likely to experience higher costs compared with economies with relatively lower fossil fuel dependence.

Figure 3.24a shows the change in GDP for World in percentage terms. These charts consider all types of intervention scenarios, i.e. those that include specific climate change targets or explicit climate change policies (ref. section 3.1.2). For more than half of the scenarios the global GDP reduction in 2100 is less than 1.5per cent. Scenarios depicting higher than 5per cent loss of GDP, include the scenarios of 550ppm or lower stabilization scenarios or scenarios where targets are stringent with less flexibilities in reduction options.

Compared to the pre-TAR, i.e., pre-SRES, SRES and post-SRES, GDP reductions are similar to the range in post-TAR scenarios. This indicates that while the new intervention scenarios may be built around different policy assumptions, for the given GHG emission reduction targets the results are robust.

Since several scenarios in the database consists information on regions, a further analysis can be done at the next level. For this analysis World is split in 'OECD' and 'Rest of the World' regions. Figure 3.24b and Figure 3.24c show the change in GDP in OECD and Rest of the World for the corresponding scenarios. It is clearly observed that GDP loss in OECD is spread over a narrower range as compared to GDP loss in the Rest of the World. The reason behind such a result in scenarios is that OECD region having already high level of development is able to switch to costly options of technology while the similar technologies when adopted in Rest of the World lead to more adjustments in the economy at the cost of development.

[INSERT **Figure 3.24** here]

Focusing on more the recent EMF-21 mitigation scenarios allows for a more standardized comparison across models and also provides for an evaluation of comprehensive, that is, multigas, mitigation targets. In the EMF-21 study, two concepts of costs were considered: reduction of GDP from a baseline scenario and the marginal costs of emission reduction. Reductions global GDP from each model's reference scenarios for stabilization target of 4.5 W/m^2 with CO_2-only mitigation, the range is from a few tenths of one per cent to over 7 per cent for 2050. For 2100, the global GDP losses range from about one-half of a per cent to just over 12 per cent. The full century long GDP effects can be seen in Figure 3.25 (Weyant and de la Chesnaye, 2005).

[INSERT **Figure 3.25** here]

When the same stabilization target is achieved through reductions of all available GHGs, that is mitigation of CH_4, N_2O and the fluorinated gases along with CO_2 from energy, the cost of achieving that target is reduced due to the more low-costs abundant mitigation opportunities in the non-CO_2 gases. Here the range is global GDP losses are from a few tenths of one per cent to just over 5 per cent for 2050. For 2100, the global GDP losses in the multigas case range from a few tenths of one per cent to under 12 per cent. See Figure 3.26 for all model data. (Weyant and De la Chesnaye, 2005).

[INSERT **Figure 3.26** here]

The increased flexibility of a multigas mitigation strategy has also significant implications for the costs of the mitigation regime. All of the EMF-21 scenarios concur that multigas mitigation is significantly cheaper than CO_2-only. The potential reductions of the marginal abatement cost ranges in the majority of the studies between 30 to 85 per cent (See Figure 3.22). The large difference in the results are mainly due to alternative choice of the baseline, and differences in modeling methodology and parameterization.

3.3.3.4 Land use

Changes in land-use practices are regarded as an important component of long-term strategies to mitigate climate change. Modifications to land-use activities can reduce emissions of both CO_2 and non-CO_2 gases (CH_4 and N_2O), increase sequestration of atmospheric CO_2 into plant biomass and soils, and produce biomass fuel substitutes for fossil fuels (Table 3.5). Available information before TAR suggested that land has the technical potential to sequester up to an additional 87 billion tonnes C by 2050 in global forests alone (Watson et al, 1995; Watson et al, 2000; Metz *et al.*, 2001). Furthermore, current technologies are capable of substantially reducing CH4 and N2O emissions from agriculture (DeAngelo *et al.*, 2004). Sectoral studies suggest that some land-based mitigation could be cost-effective compared to some traditional energy related mitigation strategies and could provide a large proportion of total mitigation (Richards and Stokes, 2004; Sohngen and Mendelsohn, 2003; McCarl and Schneider, 2001). Sohngen and Mendelsohn (2003) suggest that as much as one third of total mitigation could be provided through additional global forest sequestration.

Land mitigation scenarios have been generated by partial equilibrium and integrated assessment modeling systems capable of modeling different representations of climate policies, where partial equilibrium models have modeled carbon price trajectories and integrated assessment models have modeled climate stabilization (Table 3.6). The inclusion of land-based GHG mitigation in long-term global integrated assessment scenarios is relatively new and developing.

[INSERT **Tables 3.5 and 3.6** here]

Figure 3.27 compares a selected set of model runs by showing the price paths that have been explored in various models and the induced changes in forest area and carbon sequestration. All of the global carbon price scenarios in Table 3.6 except Sands and Leimbach (2003) evaluate incentives for forest carbon sequestration. Sands and Leimbach consider bio-energy crop incentives. To date, non-CO_2 inclusive carbon equivalent price scenarios have not been modeled with detailed global sectoral land models (see McCarl and Schneider, 2001, and USEPA, forthcoming, for U.S. examples of scenarios with land-based non-CO_2 mitigation).

[INSERT **Figure 3.27** here]

The exogenous carbon price paths are used to simulate different climate policies and assumptions. Stabilization (e.g., EMF-21, discussed below) and optimal (Sohngen and Mendelsohn, 2003) climate abatement policies suggest that carbon prices will rise over time, where the starting point and rate of increase are determined by factors such as the aggressiveness of the abatement policy, abatement option and cost assumptions, and the social discount rate (Sohngen and Sedjo, forthcoming). Rising carbon prices will provide incentives for additional forest acreage, longer rotations, and more intensive management to increase carbon storage. However, a low carbon price that is expected to rise rapidly will likely result in a postponement of additional sequestration actions until the price (benefit) of sequestration is greater, while an initially high constant price path or a slowly rising price will result in greater sequestration action in early periods (Sohngen and Sedjo, forthcoming; Sathaye *et al.* forthcoming). Even when similar price paths are run across models, model differences (e.g., structure, mitigation alternatives, available acreage, and solution method) result in different land use and sequestration responses. For example, using an identical price path of $10 per tonne carbon rising at 5per cent per year, Sathaye *et al.* (forthcoming) and Sohngen and Sedjo (forthcoming) estimated an additional 96 and 137 PgC would be stored in forests globally by 2100 respectively.

Alternatively, Sands & Leimbach (2003) evaluated biomass carbon price paths and explicitly modeled economic competition between alternative global land uses. In contrast to a sequestration policy, the incentive for biomass results in a loss of forest area leading to deforestation emissions, as forest and other lands are converted to biomass production (Table 3.6 and Figure 3.3-14). This analysis illustrates the importance of the capacity to model leakage, which can occur when a policy does not cover all emissions sources; in this case the energy mitigation policy did not include forest sequestration. Land-based leakage concerns also occur elsewhere, such as N2O emissions from intensive forest management fertilizer use and changes to crop soils. However, models do not capture all of these land-use and mitigation trade-offs yet. While leakage is not an issue in most climate stabilization scenarios since emission changes from all sources must be covered in order to achieve stabilization, the cost of stabilization (in total and the distribution of) can be affected by what is included in the set of eligible mitigation options. For example, Sands and Leimbach (2003) find that an energy CO_2 abatement stabilization policy might increase early deforestation and thereby increase the CO_2 abatement burden for industrial and energy sources.

[INSERT **Figure 3.28** here]

Some of the modeling teams in the Energy Modeling Forum Study-21 (EMF-21) directly explored this question and found that including land-use mitigation options (both non-CO_2 and CO_2) provided greater flexibility and was cost-effective for stabilizing radiative forcing at 4.5 Watts per meter squared compared to pre-industrialized times (Kurosawa, forthcoming; van Vuuren *et al.*, forthcoming; Rao and Riahi, forthcoming; Jakeman and Fisher, forthcoming). For example, Jakeman and Fisher (forthcoming) found that including land-use change and forestry mitigation options reduced the emissions reduction burden on all other emissions sources such that the projected decline in global real GDP associated with achieving stabilization was reduced to 2.3 per cent at 2050 (US$3.6 trillion in 2003 dollars), versus losses of around 7.1 per cent (US$11.2 trillion) and 3.3 per cent (US$5.2 trillion) for the CO_2-only and multi-gas scenarios respectively. A similar (but smaller) global GDP savings in 2050 associated with including land-use change mitigation was projected by Kurosawa (forthcoming), who estimated increased global forest area of over 1,000 to 1,500 billion hectares by 2100. None of the EMF-21 papers isolated the GDP effects associated with agricultural non-CO_2 abatement. However, given their small estimated share of total abatement (discussed below), the effects could be expected to be small. It is worth noting that the unique efficient mitigation approach equating marginal mitigation benefits and costs employed by Sohngen and Mendelsohn (2003) also found that the energy abatement burden was reduced when forest sequestration was permitted for optimal abatement.

The potential relative importance and timing of land-based mitigation is also important. Land-based mitigation options are thought to be cost-effective near-term abatement strategies. For example, van Vuuren *et al.* (forthcoming) project that forest sequestration will have a large mitigation role during the initial decades (as much as 40per cent of total abatement) that diminishes over time to less than 10per cent by 2100, while non-CO_2 agricultural abatement is also projected to peak in the early decades but their overall mitigation role is projected to be modest throughout the time horizon. However, Rao and Riahi (forthcoming) predict prominent roles for land-use change and forestry and biomass in overall emissions reductions, with land-use change and forestry the dominant CO_2 mitigation option under a multigas stabilization policy at over 110 GtCE and 27per cent of cumulative CO_2 reductions between 2000-2100, while biomass is the second and forth ranked option for mitigation in the CO_2-only and multigas scenarios respectively, with 19per cent and 13per cent of total CO_2 reductions over the century respectively. Like van Vuuren *et al.*, Rao and Riahi also find agricultural abatement of rice and enteric methane and soil nitrous oxide are a modest part of the cost-effective mitigation portfolio with a role that diminishes over time (10per cent of total reductions in 2020, 8per cent in 2050, 2per cent in 2100 in Rao and Riahi). Unlike van Vuuren *et al.*, Rao and Riahi expect an enduring, as well as prominent, mitigation role for land use change and forestry, less than 10per cent until 2020, but then above 10per cent for the remainder of the century, using the global forestry model of Sohngen and Sedjo (forthcoming). Sohngen and Mendelsohn (2003), using an earlier version of the Sohngen and Sedjo global forestry model to derive an optimal mitigation strategy, also projected forest sequestration to be a significant abatement strategy with the potential to account for a third of total optimal abatement over the next century, where more substantial savings from sequestration were realized during the last half of the century.

Terrestrial mitigation projections are expected to be regionally unique, while still linked across time and space by changes in global physical and economic forces. Tropical regions (South America, India, Southeast Asia, Africa) in general are expected to assume a larger share of global forest sequestration mitigation responsibility than temperate regions, a responsibility that is expected to increase over the century to approximately 65-70per cent of the additional global sequestration (Sohngen and Sedjo, forthcoming). Lower initial carbon prices can shift early period responsibility to the temperate regions since, at that time, carbon incentives are inadequate for arresting deforestation. Tropical forest mitigation activities are expected to be heavily dominated by land-use change activities (reduced deforestation and afforestation), while land management activities (increasing inputs, changing rotation length, adjusting age or species composition) are expected to be the slightly dominant strategies in temperate regions. Similar regional results are suggested by Sathaye *et al.* (forthcoming). Rao and Riahi (forthcoming) provide a rare and important glimpse into the possible regional role of land mitigation when reconciled with the full set of mitigation alternatives. Rao and Riahi discuss the different potential role of agricultural mitigation (not inclusive of bioenergy crops) across industrialized and developing country groups, finding that (a) agriculture is expected to be a larger share of the developing countries mitigation portfolio at 13per cent in 2020, 10per cent in 2050, and 3per cent in 2100 versus 6per cent, 4per cent, 1per cent respectively for the industrialized group, and (b) developing countries are likely to assume responsibility for the large majority of the agricultural mitigation (72per cent in 2020, 81per cent in 2050, and 82per cent in 2100).

In addition to GDP changes, there a number of other important outcomes from changes in land that should be tracked and reported in order to properly evaluate long-term land mitigation. As shown in the Ecosystem Assessment (2005), land use has implications for social welfare (e.g., food security, clean water access), environmental services (e.g., water quality, soil retention), and economic welfare (e.g., output prices and production).

Long-term land mitigation modeling has advanced due in large part to improvements in dynamic global modeling of land as a scarce and heterogeneous production factor, disaggregation or addition of land-using sectors in economic models, incorporation and linking of computable general equilibrium and bio-physical models in order to capture crucial dynamic feedbacks between the economic and natural systems, and initial estimates of land mitigation costs. However, at this point, the literature has yet to provide *consistent* and *complete* characterizations of the relative global and regional long-term roles of forest, pasture/range, livestock, non-energy crops, and energy crop mitigation. In particular, reconciling the large potential for additional forest sequestration with substantial projected increases in food and biomass demands is a crucial research area for future climate land mitigation modeling. Most important will be improvements in the dynamic modeling of regional land-use and land-use competition and mitigation cost estimates.

The total cost of any land-based mitigation strategy should include the opportunity cost of land, which are dynamic and regionally unique functions of changing regional bio-physical and economic circumstances. Figure 3.29 illustrates how the land mitigation portfolio can change over time with changes in the opportunity costs of land and mitigation due to rising carbon prices, 'saturating' sequestration options, changing commodity market conditions, and new technologies becoming available (USEPA, forthcoming). Modeling land-use competition will also facilitate analyses of different eligible land mitigation activities, and improvements in land mitigation integration.

[INSERT **Figure 3.29** here]

One of three approaches can be used to integrate land mitigation into climate CGE and integrated assessment models: marginal abatement/response curves (MACs; e.g., Kurosawa used MACs from DeAngelo *et al.*, forthcoming; Criqui *et al.*, forthcoming, used MACs from the Agripol global agricultural model; Jakeman and Fisher, forthcoming, used MACs from the global forestry model of Sohngen and Sedjo, forthcoming), iteration with land sector models (e.g., Sands and Leimbach, 2003; Sohngen and Mendelsohn, 2003; Rao and Riahi, forthcoming), and endogenized costs. The ideal third option requires that land input use be modelled, therefore, until recently, most models could only entertain the first or second of these options. Modeling mitigation with the third option requires different strategies and unique challenges for forestry, agriculture, and biomass. While forestry mitigation strategies are not novel, modeling forest investment behaviour requires forward thinking models. However, the novel mitigation technologies represented in agricultural MACs require the use of techniques like those employed for modeling non-CO_2 GHG mitigation for energy and industry sectors (Hyman *et al.*, 2003). Finally, biomass production is a relatively new economic sector that lacks historical data, which makes model calibration difficult.

Also necessary are improvements in mitigation cost estimates for agriculture and biomass. Livestock and crop mitigation cost estimates for specific technologies and emissions sources were not available until recently (DeAngelo *et al.*, forthcoming). However, large uncertainties still exist due to the novel and detailed mitigation technologies represented and land heterogeneity, which imply data limitations, and uncertainty about adoption and marginal responses. Biomass energy is a blossoming and promising technology and understanding of its mitigation potential will continue to grow, especially in terms of infrastructure possibilities, biomass supply requirements, and cost estimates (collection, transportation, and processing). Particularly enticing is the negative emissions strategy that combines biomass energy and geologic sequestration (e.g., Rao and Riahi, forthcoming).

In addition to addressing the basic land mitigation challenges discussed above, there are other important issues that long-term land mitigation modeling must consider. These include accounting for climate change impacts and the implications for mitigation strategies, including temperature, precipitation, CO_2 fertilization, disturbances, and interactions with tropospheric ozone (e.g., Leemans and Eickhout, 2004; Feltzer *et al.*, 2004; Sohngen *et al.*, 2001, Sands and Edmonds, 2005); understanding key baseline input sensitivities and narrowing the range of acceptable values (e.g., crop productivity in Sands and Leimbach, 2003; land supply and harvesting costs in Sohngen and Mendelsohn, forthcoming); and developing and evaluating mitigation technology assumptions for periods beyond marginal abatement curve analyses that provide estimates to 2020 or 2030.

3.3.3.5 Other agents and reactive gases

Most of the scenario studies in the literature have traditionally been focusing on CO_2 and more recently also on other non-CO_2 greenhouse gases. Quantitative analysis on global scale for the implications of climate mitigation for other agents and reactive gases, such as SO_2, NO_x, CO, VOC, BC and OC, are relatively scarce. Information on these gases is also missing in the most recent scenario database (Nakicenovic, *et al.*, forthcoming; Kainuma *et al.*, forthcoming), which was used in the previous sections to analyze scenario ranges for GHGs.

The majority of these gases belong to the group of air pollutants with local impacts on human health and the ecosystem. Reductions in GHG emissions due to climate policy can cause accompanying reductions in these gases, resulting in a broad range of ancillary benefits. These benefits have been summarized in several existing reviews (Ekins 1996, Burtraw and Toman, 1997; Burtraw *et al.* 1999; OECD 1999, Pearce, 2000). They cover not only the above mentioned emission reductions but also other related issues such as the monetary value of reduced pollution, the climatic impacts of such reductions and the improved health effects due to reduced pollution (Ayres and Walter, 1991; Heinz and Tol, 1996). In addition, they also examine other effects like employment impacts and induced technological change.

Air pollutants and greenhouse gases are often emitted by the same sources, and changes in the activity of these sources affect both types of emissions. Generally, GHG abatement measures result in shifts away from fossil fuels and reduction in inefficient combustion practices and these actions can significantly impact the intensity of pollutant emissions.

The magnitudes of such reductions strongly depends the baseline against which such ancillary benefits are measured (Morgensten, 2000). Smith *et al.* (2005) and Rao *et al.* (2005) note that with increasing incomes, there is an overall growth in environmental awareness leading to adoption of less polluting technologies also in absence of any climate policies. The pace of this trend differs significantly across pollutants and baseline scenarios.

Another critical factor for assessing the relevant ancillary benefits are current and assumed future laws, policies, and regulations (and degree of compliance) (Morgensten, 2000). In addition, the magnitude of ancillary benefits also depends to some extent on the flexibility of the climate policy mechanism.

There are a number of emission control technologies that reduce both air pollutants and greenhouse gases. Selective catalytic reduction (SCR) on gas boilers reduces not only NO_x, but also N2O, CO and CH4 (IPCC, 1997). Regular inspection and maintenance programs on oil and gas production and distribution facilities will reduce losses of CH_4, but also of other VOCs. There are, however, several examples where, at least in principle, emission control technologies aimed at a certain pollutant could increase emissions of other pollutants. For example, the substitution of gasoline engines with more fuel-efficient diesel engines might lead to higher PM/black carbon emissions (EC, 1998). The representation of such technological dynamics has traditionally been a challenge in macroeconomic top-down models. Hence, most modeling approaches that describe the relationships between GHG mitigation and pollution control employ a bottom-up, technology-rich methodology.

Most studies that examine the actual reductions in air pollutants due to climate policy have been focusing on the short term and regional or national scales. Bernow and Duckworth (1998) estimate that a policy in the USA which reduces CO_2 emissions by 10per cent by 2010 (relative to 1990) would cause reductions in SO_2 by 5.5 mt, 4 Mt of NO_x, 300,000 tpm and 75000 tVOCs. In another study, van Vuuren *et al.* estimate reduction in European SO_2 levels by 5-14per cent due to Kyoto policy implementation. Only a few studies have been exploring the long-term ancillary benefits of climate policies. For example, Rao *et al.* (2005) analyze the implications for BC and OC under a long-term climate stabilization target of 4.5 W/m^2. They find significant ancillary benefits of 5-40per cent emissions reductions for BC and OC emissions due to climate policy, the magnitude depending on the assumptions in the baseline.

The inclusion of co-benefits for air pollution can also have significant impacts on the cost-effectiveness of the climate policy being considered. There have been a number of studies examining the monetary benefits of GHG reductions and air pollutants. The policies examined in these studies include carbon taxes, mandated reductions like the Kyoto Protocol as well as stabilization of GHG concentrations. These studies report a relatively wide range of estimates of cost savings for climate policies through inclusion of the benefits of reduced air pollution. Pearce (1996) highlighted studies from the UK and Norway showing benefits of reduced air pollution that offset the costs of carbon dioxide abatement costs by between 30per cent and 100per cent. A more recent review of the literature (OECD *et al.* 2000; OECD 2002) came to similar conclusions, noting that developing countries would tend to have higher ancillary benefits from GHG mitigation compared to developed countries since they currently incur greater costs from air pollution (as reflected in socio-economic and environmental baselines for near-term development). Alcamo (2002) found that regional air pollution and climate abatement costs are strongly coupled to policy futures. To comply with agreed-upon or future policies to reduce regional air pollution in Europe, mitigation costs are implied, but these are reduced by 50-70per cent for SO_2 and around 50per cent for NO_x when combined with GHG policies (van Harmelen et al 2002). Analyses carried out under the Clean Air for Europe (CAFE) programme, suggest cost savings as high as 40per cent of GHG mitigation costs are possible from the coordination of climate and air pollution policies (Siri *et al.* 2001; Amann *et al.* 2004; Klaasen *et al.* 2004). Some of these studies are detailed below in Table 3.7.

[INSERT **Table 3.7** here]

A difficulty in evaluating the exact benefits of climate polices to air pollution is the different spatial and temporal scales of the two issues being considered. GHGs are long-lived and hence global in their impact while air pollutants are shorter-lived and tend to be more regional or local in their impacts. Swart *et al.*, 2004 stress that insight into potential synergies between climate control and air pollution needs new analytical bridges between these different spatial and temporal scales. Rypdal (2005) suggest the possibility of including local pollutants like CO and VOCs in a global climate agreement while NO_x and aerosols could be regulated by regional agreements.

Another difficulty in calculating the ancillary benefits is the large uncertainty associated with the climate effect of reduced air pollutant emissions. Some air pollutants like sulfate and carbonaceous aerosols exert radiative forcing, and thus global warming. For example, Smith *et al.* 2006 find that the attendant reduced aerosol cooling from sulfates can more than offset the reduction in warming that accrues from reduced GHGs. On the other hand, air pollutants such as NO_x, CO and VOC act as indirect greenhouse gases influencing, e.g., via their impact on OH radicals, the lifetime of direct greenhouse gases (e.g., methane and HFC). At present these effects are not considered in the majority of the ancillary benefit studies.

3.3.4 Regional and national mitigation scenarios and costs

This section reviews the recent literature on national and regional mitigation scenarios. These studies focus on a variety of issues, ranging from regional implications of climate mitigation, impact assessments, and the regional role of technology to energy security issues. In contrast to global studies, regional scenario analyses have traditionally been focusing on a more limited time horizon between 2030 to 2050.

3.3.4.1 Purpose of regional and national scenarios

There are broadly two types of national scenarios with focus on climate mitigation. First, scenarios that study mitigation options and related costs under a given national emissions caps and trade regime. And second, national scenario that focuses on the evaluation of climate mitigation measures and policies in absence of specific emissions targets. While national studies within the European Union have traditionally been focusing on the first type of analysis, the latter has mainly been explored within the U.S.A., Canada, and Japan. In addition, there is also an increasing body of literature in mainly developing countries, which explores the implications of globalization, technology transfer, socio-economic development on the national GHG emissions. Many of these analyses do not explicitly address emissions mitigation. For an overview of national and regional scenario studies see Table 3.8.

[INSERT **Table 3.8** here]

A number of scenario studies have been conducted for various countries within Europe. The studies explore a wide range of emissions caps, taking into account local circumstances and potentials for technology implementation. Many of these studies have been using specific burden sharing allocation schemes, like the contraction and convergence (C&C) approach for calculating the allocation of worldwide emissions to estimate national emissions ceilings. Several studies have explored e.g., the possibilities of expanding the share of renewable energy and the resulting prospects for establishing clean hydrogen production from renewable energy sources in Germany (Deutscher Bundestag, 2002; Fischedick, M., Nitsch, J. (eds.), 2002; Fischedick, M. *et al.*, 2004). Another European study, the COOL project (Climate OptiOns for the Long Term; xx) has explored possibilities to reduce emissions in the Netherlands by 80per cent in 2050 compared to 1990 levels. In France, the Inter Ministerial Task Force on Climate Change (MIES) (Radanne, 2004) has examined mitigation options that could lead to significant reductions in per capita emissions intensity. Savolainen, *et al.*, 2003 and Lehtila, A. *et al.*, 2004 have conducted a series of scenario analysis in order to assess technological potentials in Finland for a number of technologies, including wind power, electricity saving possibilities in household and office appliances, and emission abatement of fluorinated GHGs.

There have also been studies that have expanded the geographical scope beyond national boundaries in the European Union (Zachariadis, T. (2004), Zachariadis, T and Nikos Kouvaritakis, 2004). In particular, the European Environment Agency (EEA, 2005) reports an assessment of possible GHG gas emission reduction pathways made feasible by global action and a transition to a low-carbon energy system in Europe by 2030. The report analyses assumed EU emission reduction targets of 20 per cent below the 1990 level by 2020, 40 per cent below by 2030 and 65 per cent by 2050. It also describes the actions that could bring about the transition to a low-carbon energy system in the most cost-effective way. The domestic actions alone, based on a carbon permit price of EUR 65/t CO_2, is not sufficient for achieving the target, which reduce GHG emissions to 16-25 per cent below the 1990 level by 2030. The additional annual costs of the climate action scenario compared with the baseline scenario are projected to be about EUR 100 billion by 2030. This would represent about 0.6 per cent of EU GDP, which is projected to double between 2000 and 2030. The report concludes that a low-carbon energy system is expected to result in additional benefits, including ancillary environmental benefits, enhanced security of supply, and potential beneficial effects for employment.

A number of scenario studies in the US have been exploring the implications of climate mitigation for energy security (Hanson et al, 2004). For example, Mintzer, et al (2004) developed a set of scenarios describing three divergent paths for U.S. energy supply and use from 2000 through 2035. The scenarios are used for the identification of key technologies, important energy policy decisions, and strategic investment choices that can enhance energy security, environmental protection, and economic development.

A wide range of scenario studies have been conducted also to estimate the potential emissions reductions and the associated costs for Japan. For example, Masui *et al.* (2005) developed a set of scenarios that explore the implications of severe emissions cut-backs between 60-80per cent CO_2 by 2050 (compared to 1990). Another important study by Akimoto *et al.* evaluates the possibilities of carbon capture and storage (CCS) and the economic implications of that technology option for Japan.

National scenarios pertaining to developing countries like China and India mainly analyze future emission trajectories under various scenarios that include among others economic growth, technology development, globalization of world markets and impacts of mitigation options. Unlike the scenarios developed for the European countries, most of these scenarios do not specify limits on emissions. The study by van Vuuren *et al.* (2003) foresees large potential to mitigate carbon emissions in China, in particular through energy efficiency improvement and measures in the electricity sector. Another study from Jiang and Hu (2005) explore six energy-emissions scenarios for China. These scenarios differ from each other in terms of economic growth, technology development and government policy promoting cleaner technologies. The study shows that the contribution of technology progress in achieving a cleaner future reduces from around 50per cent in 2030 to 14per cent in 2100. Some

An increasing body of literature is exploring the implications of climate mitigation for India. For example, Shukla et al (2005) discusses the Indian GHG emissions pathways constructed along the lines of global SRES scenarios and examines socio economic and technological transitions that would underlie the different non-intervention scenarios, besides assessing how a global stabilization target such as 550 ppmv would further influence these transitions. The scenario construction for India pays specific attention to developing country dynamics underlying the multiple socio-economic transitions during the century, including demographic transitions. Another example for scenario analysis for India is the study by Nair et al (2003). They develop scenarios for the years 1995 to 2100, exploring potential shifts away from coal-intensive baselines to stabilization scenarios fostering the use of natural gas and renewables. The study by Garg *et al.* (2003) looks into the relationship between GHG emissions and local pollutants in India. They conclude that the development of GHG emissions and local pollutants will be decoupled in India. While GHG emissions are expected to continue to rise at high pace, pollutant emissions will be gradually reduced due to local pollution policies under way.

3.4 Role of technologies in long term mitigation and stabilisation: research, development, deployment, diffusion and transfer

Technology is among the central driving forces of GHG emissions. It is also one of the main determinants of economic development, consumption patterns and thus human well being. At the same time, technology and technological change offer the main possibilities for reducing future emissions and achieving the eventual stabilization of atmospheric concentrations.

In principle, there are four different ways technology can help reduce future GHG emissions:

- Improving technology efficiencies and thereby reducing emissions per unit service (output). These measures are complemented by energy conservation and rational use of energy;
- Replacing fossil intensive sources of energy by less intensive ones, such as switching from coal to natural gas. These measures can also be complemented by efficiency improvements (e.g. combined natural gas power plants are more efficient than modern coal power plants) thereby further reducing emissions;
- Introducing carbon capture and storage to abate uncontrolled emissions. This option can be applied in conjunction with all fossil energy sources and biomass (in which case it corresponds to net carbon removal from the atmosphere);
- Introducing renewable energy sources ranging from a larger role of hydro and wind power, photovoltaics and solar thermal power plants, modern biomass and other advanced technologies; and
- Enhancing the role of nuclear energy through introduction of 'inherently' safe reactors and fuel cycles, resolving the technical issues associated with long-term storage of fissile materials and improving national and international non-proliferation regimes.

Virtually all scenarios assume technological and structural changes during the century all leading to relative reduction of emissions compared to the hypothetical case of attempting to 'keep' emissions intensities and structure the same as today. Here we assume an utterly unrealistic case of 'freezing' these at current levels but letting populations change and economies develop as assumed in the original scenarios (Nakicenovic *et al.*, 2005). Figure 3.4-1 shows the resulting range of cumulative emissions between the 25th and the 75th percentile of the scenarios in the database. By doing so, we confine our analysis in this section to the central tendencies of the database scenarios, and exclude upper and lower bound outlier scenarios. These outliers, above the 75th and below the 25th percentile are discussed in more detail in the subsequent sections.

Cumulative emissions are of relevance because they in the first approximation determine the extent of anthropogenic climate change. Cumulative emissions range from 2426 (25th percentile) to 3022 (75th percentile) with a median of 2618 GtC by 2100. The next step in this energy intensity of GDP evolve as originally specified in the underlying scenarios. This in itself reduces the cumulative emissions substantively, by some 41 to 49 per cent across the range. Thus, structural economic changes lead to significant reductions of energy requirements across the scenarios as incorporated in the baselines.

This means that any mitigation measures and policies need to go beyond these baseline assumptions. The next step in this hypothetical calculation involves letting carbon intensities of energy change as originally assumed in the underlying scenarios. Again, this leads to substantial reductions of cumulative emissions, by some 46 to 53 per cent as compared to the case of no changes in neither energy nor carbon intensities as originally stipulated in the scenarios. This in fact results in the original cumulative emissions as specified by reference scenarios in the literature, from 1139 (25th percentile) to 1490 (75th percentile) with a median of 1403 GtC by 2100. It should be noted that this range is far 25th to 75th percentile only. In contrast, the full range of cumulative emissions across 56 scenarios in the database is from 807 to 3078 GtC.

The cumulative emissions range represents a huge increase compared to the historical experience. Cumulative global emissions were about 300 GtC from the 1860s to today, a very small fraction indeed of future expected emissions across the scenarios.

The next and final step is to compare the cumulative emissions in baseline scenarios with those in the mitigation and stabilization variants of the same scenarios. Figure 3.30 shows yet another significant reduction of future cumulative emissions from 783 to 1071 (corresponding to the 25th to the 75th percentile of the full scenario range) with a median of 883 GtC by 2100. This is 66 per cent reduction compared to the hypothetical case of no changes in energy and carbon intensities and still a large reduction of some 37 per cent compared to the respective baseline assumptions. In comparison, the full range of cumulative emissions from mitigation and stabilization scenarios in the database is from 256 to 1539 GtC.

[INSERT **Figure 3.30** here]

This brief assessment of the role of technology in across scenarios indicated that there is a significant technological change and diffusion of new and advanced technologies already assumed in the baselines and additional technological change ‘induced’ through various policies and measures in the mitigation scenarios.

3.4.1.1 Decarbonization Trends

Decarbonization denotes the declining average carbon intensity of primary energy over time (see Kanoh, 1992). Although the decarbonization of the world’s energy system is comparatively slow (0.3 per cent per year), the trend has persisted throughout the last two centuries (Nakicenovic, 1996). The overall tendency toward lower carbon intensities is due to the continuous replacement of fuels with high carbon content by those with low carbon content; however, intensities are currently increasing in some developing regions.

The carbon intensities of the full scenario sample as well as for intervention and non-intervention scenarios are shown in Figure 3.31, 3.32, and 3.33 respectively. Like in the previous two sections of this chapter, we compare the range of the scenarios in the literature until 2001 with recent projections from scenarios developed after 2001 (Nakicenovic *et al.*, 2005).

The majority of the scenarios developed pre and post 2001 show a similar and persistent decarbonization trend. In particular, the medians of the scenario sets indicate decarbonization rates of about 0.9 (pre 2001) and 0.6 (post 2001) which is a significant increase compared to the historical rates of about 0.3 per cent per year.

The scenarios that are most intensive in use of fossil fuels lead to practically no reduction in carbon intensity. For example, the upper bound of the recent scenarios developed after 2001 depict slightly increasing (about 0.3 per cent per year) carbon intensities (A2 reference scenario, Mori, 2003, see figures comparing carbon emissions across scenarios in the literature presented in the previous two sections). Most notably, a few scenarios developed before 2001 follow a path that is opposite from other scenarios: decarbonization of primary energy with decreasing energy efficiency until 2040, followed by rapidly increasing ratios of CO_2 per unit of primary energy after 2040 - in other words, re-carbonization. These scenarios lie in the long-term well above the range spanned by the new scenarios, indicating a shift towards more rapid CO_2 intensity improvements in the recent literature (Nakicenovic *et al.*, 2005).

The highest rates of decarbonization (up to 2.5 per cent per year for the recent scenarios) are from scenarios that envision a complete transition in the energy system away from carbon-intensive fossil fuels. Clearly, the majority of these scenarios are intervention scenarios, although also some non-intervention scenarios show drastic reductions in CO_2 intensities due to other reasons than climate policies (e.g., the combination of sustainable development policies and technology push measures to promote renewable hydrogen systems, Barreto *et al.*, 2003). The relatively fast decarbonization rate of intervention scenarios is also illustrated by the median of the post 2001 intervention scenarios, which depict an average rate of improvement 1.1 per cent per year over the course of the century, compared to just 0.3 per cent for the non-intervention scenarios. Note, nevertheless, the modest increase in carbon intensity improvements in the intervention scenarios above the 75 per centile of the distribution of the recent scenarios (Figure 3.4-3). The vast majority of these scenarios represent sensitivity analysis; have climate policies for mitigation non-CO_2 greenhouse gases emissions (methane emissions policies: Reilly *et al.*, forthcoming); or have comparatively modest CO_2 reductions measures, like the implementation of a relatively minor carbon tax of $10/tC over the course of the century (e.g., Kurosawa, 2004). Although these scenarios are categorized according to our definition as intervention scenarios, they do not necessarily lead to the stabilization of atmospheric CO_2 concentrations.

[INSERT **Figure 3.31** here]
[INSERT **Figure 3.32** here]
[INSERT **Figure 3.33** here]

3.4.1.2 Key factors for carbon free energy and decarbonization development

All of the technological options assumed to contribute toward further decarbonization and reduction of future GHG emissions require further research and development (R&D) to both improve their technical performance, reduce costs and achieve social acceptability. In addition, deployment of carbon-saving technologies needs to be applied at ever larger scales to benefit from potentials of technological learning that can result in further improved costs and economic characteristics of new technologies. Most importantly, appropriate institutional and policy inducements are required to enhance widespread diffusion and transfer of these technologies.

The full replacement of dominant technologies in the energy systems is generally a long process. In the past, the major energy-technology transitions have lasted more than half a century such as the transition from coal as the dominant energy sources in the world some 80 years ago to dominance of crude oil during the 1970s. Achieving such a transition in the future toward lower GHG intensities one of the major technological challenges addressed in mitigation and stabilization scenarios.

3.4.2 RD&D and investment patterns

3.4.2.1 Summary of RD&D

In 1998 the 29 OECD countries spent $520 billion on research and development—more than the combined economic output of the world' 30 poorest countries.10 Over the past 10 years a growing portion of that research has been funded by the private sector. Yet despite such high investment, research remains woefully inadequate for the technologies most needed for development.

The private sector is leading global research and development, and has much of the finance, knowledge and personnel for technological innovation. Among most OECD countries the private sector finances 50–60 per cent of research and development. Firms play an even bigger role in research and development in Ireland, Japan, Korea and Sweden. In most countries corporations implement more research than they fund, indicating that there is some government funding of corporate research and development. Universities typically undertake 15–20 per cent of national research and development in technology and biotechnology that matters so much for human development.

Worldwide, the pharmaceutical and biotechnology industries spent $39 billion on research and development in 1998. Research-based pharmaceutical companies in the United States invested $24 billion in 1999, increasing to $26.4 billion in 2000. Since the mid-1990s the top 20 pharmaceutical companies have doubled their spending on research and development. If that trend continues, average spending per company could rise to $2.5 billion by 2005.

3.4.2.2 Needs for RD & D

Accelerating the availability of advanced and new technologies will be central to greatly reducing CO_2 emissions from energy and other sources. Innovation in energy technology will be integral to meeting the objective of emission reduction. Support will be needed for all components of the innovation system – research and development (R&D), demonstration, market introduction and its feedback to development, flows of information and knowledge, and the scientific research that could lead to new technological advances. Sufficient investment will be required to ensure the best technologies are brought to market in a timely manner.

Up to 2050, known technologies can be readied to achieve deep cuts in CO_2 emissions. Beyond then, more fundamental changes in energy technologies will be required. Even known technologies may require extensive changes to bring their costs within reach. Basic research in areas as diverse as biological processes, plasma physics and nanoscience will be part of an integrated approach to meeting climate change objectives over a 100-year time horizon.

3.4.3 Dynamics and drivers of technological change, barriers (timing of technology deployment, learning)

3.4.3.1 Summary from TAR

IPCC-TAR concluded that reduction of greenhouse gas emissions is highly dependent upon both technological innovation and practices. The rate of introduction of new technologies, and the drivers for adoption are however different in industrial market economies, economies in transition and developing countries. This is to an extent reflected in global emissions scenrios as they often involve technological change at a level of a dozen or so world regions. This usually involves make more region-specific assumptions about future performance, costs and investment needs for new and low-carbon technologies.

There are multiple government-driven pathways for technological innovation and change. Through regulation of energy markets, environmental regulations, energy efficiency standards, market-based initiatives such as energy and emission taxes, governments can induce technology changes and influence the level of innovations. In emissions scenarios, this is reflected in assumptions about policy instruments such as taxes, emissions permits, technology standards, costs, lower and upper bounds on technology diffusion.

3.4.3.2 Learning-by-doing

The performance and productivity of technologies typically increase substantially as organizations and individuals gain experience with them. Such improvements reflect organizational and individual learning. Learning can originate from many sources – through sources outside the organization, through sources within the organization, through improving ‘know-how’, or through improving design features and economies of scale.

The view that technology deployment in the marketplace – not only research and development efforts – is a key element to speed up technical change, is borne out by lessons from past technological developments. They reveal that the costs of technologies decrease as total unit volume rises. The metric of such change is the 'progress ratio', defined as the reduction of cost as a consequence of the doubling of cumulative installed technology. This ratio has proven roughly constant for most technologies – although it differs significantly from one technology to another.

This 'learning-by-doing' concept of technical change provides a strong argument in favour of global early action. However, it does not provide guidance on how to induce change – i.e., what policies to adopt to make new, climate-friendly technologies fully economically competitive (IEA, 2002).

3.4.3.3 Barriers of Technology transfer, diffusion and deployment for long term mitigation

Barriers to the transfer of ESTs arise at each stage of the process. These vary according to the specific context from sector to sector and can manifest themselves differently in developed and developing countries, and in EITs. These barriers range from lack of information; insufficient human capabilities; political and economic barriers, such as lack of capital, high transaction costs, lack of full cost pricing, and trade and policy barriers; institutional and structural barriers; lack of understanding of local needs; business limitations, such as risk aversion in financial institutions; institutional limitations, such as insufficient legal protection; and inadequate environmental codes and standards.

One of the most obvious barriers to using innovation to address GHG emissions is the lack of incentives. Economic, regulatory, and social incentives for reducing GHG emissions will also act as incentives for innovation to find new means of mitigation. Another important type of barrier, which both slows technological change in general and tends to skew it in particular directions, is that posed by 'lock-in'.

3.4.3.4 Dynamics in developing countries and timing of technology deployment

National policies in developing countries necessarily focus on more fundamental priorities of development such as poverty alleviation and providing basic living conditions for their populations and it is unlikely that in the short term national policies would be driven by environmental concerns. However for the medium to long term some optimism can certainly be justified. The success of policies that address short-term development concerns would determine the pace at which convergence of the quality of life in the developing and the developed world would occur over the long term.

Development goals in many ways are driving endogenous changes. The end-result of the process of development is presence of efficient markets and institutions but development goals will have to be delivered regardless of whether markets are developed or not in the meanwhile. For long-term scenarios, unfolding of key drivers depends on inherent uncertainties of the exogenous changes such as in technology and behavioural or social, endogenous policies those are driven by 'development goals' and the induced change from climate policies. The three 'changes' are simultaneous and inseparable within the context of development. The development policies adopted are like climate opportunities, as they generate endogenous changes and create a path dependence for stabilization induced technological change (Shukla *et al.*, 2005).

3.4.3.5 Dynamics technology across recent emissions scenrios

Technological change is treated largerly as an exogenous assumption abut costs, market penetration and other technology characteristics in emissions scenarios (Barker *et al.*, 2005). Hourcade and Shukla (2001) review modelling studies of costs of stabilisation in post-SRES mitigation scenarios from top-down general economic models and report the results of a model comparison study. They identify widely differing costs of stabilisation at 550 ppmv by 2050 of between 0.2 to 1.75 per cent GDP, mainly influenced by the size of the emissions in the baseline. Hourcade and Shukla (2001) indicate that technology assumptions play a critical factor affecting the timing and cost of cost-effectiveness of emission abatement in the model. The studies incorporating induced technological change (ITC) suggest that this could reduce stabilization costs substantially: ITC greatly broadens the scope of technology-related policies and usually increases the benefits of early action, which accelerates development of cheaper technologies (Barker *et al.*, 2005; Gritsevskyi and Nakicenovic, 2000). This is due to the cumulative nature of ITC as treated in the new modelling approaches. Early deployment of costly technologies leads to the benefits of learning and lower costs as diffusion progresses. In contrast, scenarios with exogenous technology assumptions imply waiting for better technologies to arrive in the future.

More recent work seems to confirm these findings (Barker *et al.*, 2005). For example, Manne and Richels (2004) and Goulder (2004) also found that ITC lowers mitigation costs and that more extensive reductions in GHGs are justified than with exogenous technical change. Nakicenovich and Riahi (2003) noted how the assumption about the availability of future technologies was a strong driver of stabilisation costs. Edmonds et al (2004) studied stabilisation at 550 ppmv CO_2 in the SRES B2 world using the MiniCAM model and showed a reduction in costs of a factor of 2.5 in 2100 using a baseline incorporating technical change. Edmonds considers that advanced technology development to be far more important as a driver of emission reductions than carbon taxes. Van Vuuren et al (2004) also concluded that technology development is a key in achieving emission. Weyant (2004) concludes that stabilisation will require development on a large scale of new energy technologies and that costs would be reduced if many technologies are developed in parallel and there is early adoption of policies to encourage technology development.

The results from the bottom-up and more technology-specific modelling approaches give a different perspective. Following the work in particular of IIASA (e.g. Grubler, 1999), models investigating induced technical change emerged during the mid- and late 1990s. These models show that ITC can alter results in many ways. Nakicenovic and Riahi (2003) also note the great significance of the choice of baseline scenario in driving stabilisation costs. In the previous sections of this chapter, it was also illustrated that the baseline choice is crucial in determining the nature (and by implication also cost) of stabilization. However, this influence is itself largely due to the different assumptions made about technological change in the baseline scenarios. Gritsevskyi and Nakicenovic (2000) identified some 53 clusters of least-cost technologies allowing for endogenous technological learning with uncertainty. This suggests that a decarbonised economy may not cost any more than a carbon-intensive one, if technology learning curves are taken into account. Other key findings are that there is a large diversity across alternative energy technology strategies, a finding that was also reached in more recent scenario literature (Barker *et al.*, 2005). These results suggest that it is not possible to choose an ‘optimal’ direction of energy-system development. TAR on such modelling suggests (Watson *et al.*, 2001) that up to 5GtC a year reduction by 2020 (some 50 per cent of baseline projections) might be achieved by current technologies, half of the reduction at no direct cost, the other half at direct costs of less than US$100/tC-equivalent.

3.5 Interaction between mitigation and adaptation, in the light of climate change impacts and decision making under long run uncertainty

Given the inertia of the climate system, even drastic cuts in greenhouse gas emissions would do little to alter the path of climate change in coming decades, as these changes are being driven by the increase in the atmospheric concentrations of greenhouse gases that has occurred over the past two centuries. The portfolio of possible responses to climate change include: adaptation – actions that help human and natural systems to adjust to climate change; mitigation – actions that reduce greenhouse gas emissions, or remove greenhouse gases from the atmosphere and thus limit long-term climate change; and technology R&D and institutional innovations (independent of direct response to climate change) that may enhance both the capacity to adapt to and mitigate the effects of climate change in the future.

Incomplete understanding of both the magnitude and timing of climate change, its likely consequences, and the differing levels of efficacy of the various counter measures presents a range of difficulties for decision-makers. In addition, climate change decision-making is not a once-and-for-all event. Rather it is an iterative process that is likely to take place over decades if not centuries where there will be opportunities for learning and mid-course corrections in light of new information. These long term inter temporal issues are further explored in section 3.6.

3.5.1 The interaction between levels of mitigation and adaptation

Implicitly, at each point along the decision time path, tradeoffs will be made between the level of mitigation, investments in adaptation and the amount of residual climate impacts that society is either prepared or forced to tolerate in an effort to find an appropriate mix of near term actions. These actions will be complemented by continued climate change research to reduce uncertainties and better inform future policy decisions.

The bulk of the policy assessment to date has been devoted to the links between mitigation policies and a wide range of emission and climate scenarios, rather than to adaptation. There are a number of reasons for this. First, the focus of the international community has largely been on mitigation although the importance of adaptation is underlined in Article 4 of the UNFCCC and Article 10 of the Kyoto Protocol (Yamin and Depledge, 2004; Depledge, 2000).

Second, adaptation is largely undertaken at the local level, often by individuals. It is therefore not the primary concern of the international community. In addition, it is difficult to make generalisations about the optimal level of adaptation or the ways in which individuals or communities are likely to adapt given the context specific nature of adaptation options. Uncertainty about future returns at the enterprise level means that there is an ‘option value’ associated with postponing new investment. The potential cost associated with making a poor or irreversible investment can be reduced by delaying an investment decision and waiting for improved information about future climate and therefore project outcomes. This means that the expected return from an investment required to compensate investors may include not only the direct opportunity cost of capital, but also the costs associated with committing to an irreversible investment and losing the option to wait for better information. Consequently, uncertainty about climate change will slow down the rate of long term investment in adaptation strategies (Kokic *et al.* 2005).

Finally, although the data are improving, detailed climate and impact assessments at the regional and local scale are available only for a few locations (e.g. Hayoe et al, 2004; West and Gawith, 2005; Cohen *et al.*, 2005).

One of the methodological challenges in determining the optimal trade off between the levels of mitigation and adaptation is valuing the damages (impacts) of climate change. Many authors point to the need for monetized metrics of climate change impacts and their economic consequences in formal policy analysis (Tol *et al.*, 2000; Rothman 2000; Jacoby 2004; Pearce 2003). Others argue for the use of a range of different monetary and physical impact metrics (see **Table 3.9**) to inform policy decisions (Patwardhan *et al.* 2004; Schneider *et al.* 2000; Corfee-Morlot and Hoehne 2003; Smith *et al.*, 2001). Faced with an array of monetary and non monetary indicators of climate impacts analysts and decision makers are likely to make a number of subjective assessments. What matters in reporting results is to summarise the subjective judgements that are used to construct the estimates and to be capable, using aggregated values, to trace them back to original physical impact data (Azar 1998; Schneider 2004; Schneider *et al.* 2000; Moss and Schneider 2000).

[INSERT **Table 3.9** here]

Another methodological issue that arises in assessing mitigation/adaptation trade offs is the effect of assumed functional forms on the outcome. The consequences of the choice of functional form are well understood in economics (for example see [reference to be inserted]. In the case of climate analysis the functional form of the damages function will be an important determinant of the inter temporal distribution of damages and therefore the optimal policy response conditioned on that damages function. In the literature there are few estimates of climate impacts at a range of temperatures. Often damage functions are extrapolated from one or two benchmark estimates – typically a no climate change case, and at doubling of CO_2 concentrations (e.g, Tol 2002b). Pearce (1996) reviewed estimates of climate impacts on the US economy and many functional forms are calibrated using these estimates. Extrapolation in this case implies that a functional form has to be assumed from only two data points. That is, the functional form is derived by assuming zero impacts today and drawing a line or curve to the estimated impacts at some static point in the future (Rothman 2000). An assumption of linearity in a damage function would imply greater near term dangers than an assumption of a cubic function (Courtois 2004) leading to greater optimal near term emission reductions, and vice versa. Roughgarden and Schneider (1999) reformulated Nordhaus' DICE model to show that with alternative, yet equally plausible, damage estimates a significantly more aggressive optimal policy is obtained thus highlighting the importance of taking care in choice of functional form.

Impact assessments and the damage cost functions used in integrated assessment models often address adaptation in only a limited way. In some literature on damage costs, failure to consider adaptation may have led to an over-estimation of impacts and damage costs (Tol *et al.* 2000; Callaway 2004). In other studies it has been assumed that farmers have full information to switch crops and to adapt in an optimal manner to CO_2 fertilisation (Mendelsohn 2000): this treatment of adaptation is likely to overestimate the effectiveness of adaptation and underestimate its costs by ignoring the need for learning and transaction costs (Tol *et al.* 2000; Tol 2002b).

Finally most assessments may not have adequately accounted for how development could reduce (or increase) the impacts of climate change and adaptive capacity (Tol 2000; Tol *et al.* 2004; Rothman 2000; Smith *et al.* 2001; Hitz and Smith 2004). For example, there are large path dependencies that result in estimates of climate impacts being dependent on assumptions about development, population and demographics, technology and infrastructure, institutional and adaptive capacity. Parry (2004) shows the socioeconomic impacts of climate change due to water resource depletion, flooding, drought, hunger, sea level rise and the spread of vector borne disease differ with baseline assumptions.

3.5.2 Avoided climate change, impacts and damages from recent mitigation emission scenarios

[INSERT **Table 3.10** here]

Table 3.10 (yet to be developed) shows the conceptual summary of the impacts avoided by moving from a baseline scenario (such as SRES A1F1) to a stabilisation scenario (550 ppm CO_2). These estimates of avoided impacts, damage and mitigation costs are derived from the integrated assessment literature using different emission scenarios, many of which are documented in the scenario database referred to earlier (see also individual references in last column for each entry). Avoided impacts are based on a comparison of estimated impacts under the stabilisation (or mitigation) scenario to those described under the baseline scenario. One can see shifts in the avoided impacts performance of different mitigation scenarios compared to baseline by looking across various stabilisation scenarios with a particular baseline group (i.e. across the rows for each baseline + stabilisation set). After Swart *et al.* (2002), it is also possible consider avoided impacts from mitigation as implied from the baseline scenario literature alone, e.g. by comparing the climate changes and impacts associated with the envelope of emission baselines ranging from the higher emission baselines (e.g. A1F1 or A1B where climate changes are similar to 750ppm CO_2 stabilization scenario) to intermediate baseline (e.g. B2, similar to 650ppm) and lower baselines (e.g. B1, similar to 450ppm CO_2). This approach was demonstrated in an assessment of climate changes and impacts in California under different emission scenarios (Hayhoe *et al.* 2004).

3.6 Linkages between short-term emissions trends and envisaged policies and long-term climate policy targets

Determining the appropriate timing of climate policies, or various components of these policies, is greatly complicated by long run uncertainties surrounding key socio-economic drivers such as population growth, economic growth, technology development and diffusion; and uncertainties about scientific phenomena including the carbon cycle, climate sensitivity and ecosystem vulnerability in relation to long term climate change. The crux of the matter, in terms of public policy, is to synthesise the available information in a sequential decision-making framework accounting for the progressive revelation of information on each of the determinants of the costs and benefits of alternative policies.

In the third assessment report of the IPCC, this synthesis (chapter 8 on 'costs and ancillary benefits of mitigation' and chapter 10 on 'decision-making frameworks') was focused on clarifying the implications of various decision-making approaches used to capture climate risks. A second significant insight was how specification of technical change in terms of an autonomous process (function of time), an R&D induced process or a cumulative learning process affects the timing of abatement.

A significant amount of material has been produced since TAR about these parameters and it has been used to upgrade our understanding of the appropriate timing of climate action. The main areas that have been the focus of research are reviewed below.

3.6.1 Factors affecting timing of climate policy actions

This section reviews recent information with respect to parameters that are critical to the timing of mitigation action. Factors include the influence of the metric used to capture climate risks; the choice of discount rate; insights given by alternative decision frameworks, namely cost-efficiency and cost-benefit analysis; the effect of technical and socio-economic system dynamics on short term mitigation efforts; and the influence of non-CO_2 gases and sequestration options on the time profile of decarbonisation efforts.

3.6.1.1 The influence of metrics used to capture climate risks

In attempts to find an optimal policy path for climate action, ‘optimal control models’ may be used to maximise total welfare under certain income and climate constraints and conditions. Two approaches to this type of modelling may be employed: monetary estimates of the economic and social damages caused by climate change to assist in finding the optimal emissions pathway under a cost-benefit analysis by equating the marginal discounted sums of mitigation costs and climate damages; or use of various forms of climate constraints from simple concentration ceilings to temperature targets with or without constraints on the rate of global warming.

The two methods represent different ways of dealing with climate risks. Using a set of environmental constraints is a way of considering that the threat of climate change might become unacceptable to society beyond such constraints, whereas a money metric valuation approach translates the same expectations via damage curves with dangerous thresholds. The main source of divergence between the two approaches is the discount rate - within a cost-efficiency framework, environmental constraints are not influenced by discounting; conversely, in a cost-benefit framework, benefits occur later than costs and thus have a lower weighting. The extent of this trade off depends on the level of the discount rate.

3.6.1.2 Discounting and timing of action

Climate policies have consequences for both present and future generations and any decision reflects an implicit or explicit weighting of generations. To a large extent, the discount rate makes this weighting explicit. Controversies about the appropriate level of discount rate have been thoroughly examined in the SAR and the TAR.

Most concerns about the use of non-zero discount rates arise as a result of uncertainty about the future. The discount rate can affect valuation of the environment relative to consumption, and it is often assumed that over the long run, economic growth is associated with an increase in the relative value of the environment. Guesnerie (2005) and Tol (1994) find that a plausible ‘ecological discount rate’ is close to zero provided that there is concern for intergenerational equity and that the environment is considered as a ‘superior good’ to which future and richer generations will give a higher per centage of income.

Environmental value is also affected by the time profile of environmental damages, which is largely determined by the shape of the function deriving damages from cumulated emissions. Lecocq and Hourcade (2003) demonstrate that the steeper the damage function, the lesser the influence of the discount rate on short-term abatement.

Time preference for the present takes place amongst a set of other key parameters such as marginal productivity of capital, technical progress and distribution of probabilities on key economic and environmental parameters. This creates a complex link between the level of discount rate and the short term level of protection of the environment and makes the overall effect of the discount rate choice ambiguous in many instances. For example, high growth scenarios imply optimistic assumptions on the marginal productivity of capital leading to high discount rates; but if such scenarios are run under the assumption of damage thresholds, these thresholds are crossed sooner than in low growth scenarios, which partly compensates the impact of higher discount rates.

Heal (2001) establishes that the social discount rate should be higher for a stock-dependent utility function where lower environmental quality negatively affects the welfare derived from consumption. As such, capital investments are justified only if they yield a higher consumption flow, since the utility of this flow is lowered by associated environmental degradation. But the higher discount rate results in a lower long term growth and a higher level of environmental protection.

The influence of discount rates on short term decisions is thus more complex than often suggested.

3.6.1.3 Influence of concentration or temperature targets in a cost-effectiveness framework

Within a cost-efficiency framework, the aim is to minimize the cost of the mix of options (mitigation and sequestration, technology R&D) needed to remain inside the 'tolerable space'. Since the tolerable space is currently unknown, setting it to a specific value is not independent of diverse value judgments and is unlikely to gain social consensus.

The key issue is the difference between the optimal timing of abatement under a 'certainty case', when the ultimate target is known from the outset, and under a 'probabilistic' case, where decision makers account for the fact that the level of a 'dangerous interference' will be progressively revealed and calibrate the policy response accordingly. In the latter case, the choice of abatement path involves balancing the economic risks of rapid abatement now (that premature capital stock retirement will later be proved unnecessary) against the corresponding risks of delay (that more rapid emission reduction will be required later, necessitating premature retirement of a greater proportion of future capital stock) *(SAR,WGIII, SPM).*

Under a Tolerable Windows Approach [Petschel-Held *et al.*, 1999; Toth *et al.*, 1997] or a Safe Landing Approach [Alcamo et Kreileman, 1996; Swart *et al.*, 1998] significant efforts have been carried out to explore climate policies focusing on global mean temperature. Concentrations ceilings are a poor surrogate for what constitutes dangerous climate change: they by-pass many links from atmospheric chemistry to damages and propagate uncertainty, and they explicitly refer only to long-term climate targets. By contrast, global mean temperature (GMT) is a better and more tangible proxy of climate change impacts [McCarthy *et al.*, 2001]. Moreover, this proxy for climate damages takes into account the rate of climate change, a major determinant of impacts, both for ecosystems and technical systems.

In terms of sequential decision-making under uncertainty, using temperature ceilings presents the advantage of dealing explicitly with uncertainty regarding climate sensitivity. The TAR states that '*the equilibrium climate sensitivity was estimated to be between +1.5°C and +4.5°C in the SAR. This range still encompasses the estimates from the current models in active use*' (Houghton *et al.*, 2001, chap. IX, p. 561). Wigley and Raper (2001) have proposed an *ad hoc* lognormal distribution, with a 90 per cent confidence range from 1.5°*C* to 4.5°*C*. Since then, significant research has better characterised climate sensitivity and quantified its uncertainty[1] but this parameter is hard to constrain, either from observations (because historical radiative forcing and ocean heat uptake data are poor) (Andronova et Schlesinger, 2001; Forest *et al.*, 2002; Gregory *et al.*, 2002; Knutti *et al.*, 2002, 2003; Frame, 2005) or from atmosphere-ocean global circulation models (because the parameterisations of some key processes such as cloud effects need improving) (Murphy, 2004; Stainforth, 2005). These studies have produced new estimates which remain concentrated over the +1.5°*C* +4.5°*C* range with a mean close to +3.5°*C* but they indicate that one cannot exclude much higher values, admittedly with low probabilities.

Studies exploring the implications of this uncertainty for decision making (Caldeira *et al.*, 2003; Kriegler et Bruckner, 2004; Lempert *et al.*, 1994; Hammitt *et al.*, 1992; Den Elzen and Meinshausen 2005) conclude that the lower the warming threshold and the higher the climate sensitivity (both implying stringent concentrations ceilings), the narrower the global carbon budget.

A few authors go beyond such sensitivity studies to incorporate not only the consequences of uncertainty about climate sensitivity but also the consequences of revising it given improvements in knowledge. To analyse the trade-off between a costly acceleration of mitigation costs and a (temporary) overshoot of targets and the climate impacts of this overshoot, some form of cost-benefit analysis is required. Ambrosi *et al.* (2003) did so through a willingness to pay for not interfering with the climate system. They show that allowing for an overshoot of the ex-ante target significantly decreases the required acceleration of decarbonisation and the peak of abatement costs but does not change drastically the level of abatement prior to the revelation of information.

Furthermore, uncertainty about climate sensitivity magnifies the influence of the rate constraint on short-term decision making, leading to rather stringent policy recommendations for the coming decades (Ambrosi, 2005). Earlier emissions reductions are found optimal to hedge against eventual high climate sensitivity, which is associated with faster and more intense warming. This result is robust to the choice of discount rate and to beliefs about climate sensitivity.

Ambrosi (2005) shows that uncertainty about the rate constraint is even more important for short-term decision making than uncertainty about climate sensitivity or the magnitude of warming. Therefore, research should be aimed at better characterising climate change risks with a view to help decision-makers in agreeing on a safe guardrail to limit the rate of global warming.

3.6.1.4 Implications of assumptions concerning cost-benefits functions

In the TAR, the pioneer attempts to assess hedging strategies in a cost-benefit framework tended to conclude that there was need for a limited short-term abatement effort. This conclusion conforms to intuition since discounted damages occurring some decades in the future are easily outweighed by nearer term abatement costs. However, this result is strongly dependent on the assumptions about the shape of the damage curve, especially with regard to the way it translates non-linear events, singularities and catastrophes – concerns about which cost-benefits analyses of climate policies have only recently come to focus.

With damage functions exhibiting smooth and regular damages (such as power functions with integer exponents or polynomial ones), GHG abatement is postponed because during several decades the temporal rate of increase in marginal climate change damage remains far lower than the discount rate (which lowers the marginal damages profile over time). Since most studies are calibrated on a single point, the paradox is that, the higher the exponent (to account for possible catastrophic damages for intense warming) the lower are the damages over the short and medium term, and, consequently, the sum of discounted damages. To factor in costs of major environmental risks triggered by climate change, Nordhaus and Boyer (2000), for instance, increase the scale coefficients of their damage functions without altering their shapes – as a result, their models still recommend low short-term abatement effort. In fact, such standard damage functions capture high impact scenarios rather than true climate catastrophes.

Such non-linear singularities may stem from large-scale catastrophic events such as slow-down of the THC. Recent modelling has shown that including even small probabilities of catastrophic events may substantially alter near term optimal emissions targets and raise the optimal carbon tax (Mastrandea and Schneider 2004; Azar and Lindgren 2003) Azar and Schneider (2001) conclude that cost-benefit analysis can justify any emission reduction targets if 'nasty surprises' in the climate system are considered. Ingham and Ulph (2004) and Howarth (2003) report similar findings. But these surprises may be caused by other channels than large catastrophic events. For example, they may be triggered by smooth climate changes that exceed a vulnerability threshold (for example, shocks to agricultural systems in developing countries leading to starvation).

Two approaches have been used to scrutinise the impact of such singularities on the timing of action, leading to similar conclusions. Keller *et al.* (2004a,b) explore the combined effects of uncertainty about climate sensitivity and irreversible damage (triggered by a potential ocean thermohaline circulation collapse) to show that significant emissions reductions may be justified to avoid or delay even small damages from an uncertain and irreversible climate change—even when future learning about the system is considered. Together with this general conclusion, they point out the seemingly paradoxical result that the optimal policy is not independent of uncertainty or belief about climate sensitivity and damages: if a climate catastrophe seems very likely within a rather near time horizon, it might be considered economically sound to accept the consequences of the catastrophe instead of investing in expensive mitigation to avoid the inevitable. Similarly, under a cost-effectiveness approach, societies faced with a very tight environmental constraint would prefer a temporary overshoot in emissions in the near term rather than bear the social costs of an exaggerated reduction in emissions. This result points to the existence of a window of opportunity for precautionary abatement measures.

Ambrosi *et al.* (2003) focus on the interplay between uncertainty about climate sensitivity and the eventuality of a threshold in climate change damages. They demonstrate that given the uncertainty about climate sensitivity (which brings closer the time when the vulnerability threshold may be exceeded), abrupt damages compared to smooth and regular ones imply early mitigation efforts; meanwhile, there exists a window of opportunity to learn before 2040 the value of climate sensitivity. Furthermore, even small expectations regarding the eventuality of abrupt damages justify anticipating emissions reductions (also established by Dumas and Ha-Duong (2004). These conclusions converge with results in the literature on investment under uncertainty obtained by Baranzini *et al.* (2003). These authors find that gradual, continuous uncertainty in the global warming process is likely to delay the adoption of abatement policies (as found with the standard CBA applied to climate change policy) but that the possibility of climate catastrophes accelerates the implementation of these policies as their net discounted benefits increase significantly.

3.6.1.5 Influence of the representation of investment dynamics, socio-economic inertia and technical change

Some models treat technical change as an autonomous process independent of time (ATC). The implication of this is that today's decisions have no effect on the future technology mix. Other models represent technical change as induced by today's policies (ITC) either as a consequence of R&D funding or learning by doing (LBD).

Moving from an ATC to an ITC view of technical change forces a distinction between the timing of action (launching a price signal, an R&D program) and the timing of GHG abatement.

As a result of inertia in technology, near term actions are required to abate in the future. As such, abatement in any given period is not necessarily a good indicator of effort on abatement in the same period. Studies incorporating ITC suggest that addressing climate change - including atmospheric stabilization - could become cheaper in the long run. ITC greatly broadens the scope of technology-related policies and usually increases the economic benefits of early action, which accelerates development of cheaper technologies. This contradicts results from models with autonomous technical change (ATC), which can imply the best policy is waiting for better technologies to arrive. Other recent studies highlighting the importance of the role of technological change (Manne and Richels, 2004; Goulder 2004) find that ITC lowers mitigation costs and justifies more extensive reductions in GHG than with ATC. Nakicenovic and Riahi (2003) examine the costs of attaining stabilisation targets of 400 and 450 ppm CO_2, and note that assumptions about the availability of future technologies is a strong driver of stabilisation costs.

Hourcade and Shukla (TAR/WGIII/chap VIII) reviewed empirical studies of costs of stabilisation in post SRES mitigation scenarios. As Hourcade and Shukla point out, one of the most critical factors in determining the timing of emission reductions and their costs in modelling is the role of technological change. The Stanford Energy Modelling Forum has also compared the results of 6 integrated assessment models used to study stabilisation (Peck and Teisberg, 1995; Tol 1999a; Manne and Richels, 2001; Richels and Edmonds, 1995). The modelling output highlights a considerable uncertainty in cost-estimates, with differing implications for the dynamics of emission reductions. Nakicenovic and Riahi (2003) also note the significance of the choice of baseline scenario in driving stabilisation costs. However, this influence is itself largely due to the different assumptions made about technological change in baseline scenarios.

The degree to which lower costs are associated with delay in emission reductions also depends crucially on other aspects of the treatment of technical change. Grubb (1997) and Kypreos and Barretto (1999) studied how induced technological change and learning by doing processes facilitate cost-effective emission reductions at an earlier date than would otherwise be the case.

Public policy to reduce emissions needs to be combined with incentives for technological innovation. Technologies for GHG mitigation was the subject of a recent study by the Energy Modelling Forum (EMF 19) introduced in Weyant (2004). The overall conclusion of this study is that stabilisation will require large scale development of new energy technologies that will require considerable expenditure over a long time horizon (‘many decades’) to implement. Costs are reduced if many technologies are developed in parallel and there is early adoption of policies to encourage technology development.

Since the TAR some efforts have been devoted to understanding how different views about the driving forces of technical change lead to different policy conclusions. Two main parameters have been scrutinised in recent studies with ITC, the timing of abatement and the time profile of the implicit carbon tax. Mostly for the sake of clarity, studies have analyzed the impact of R&D and LBD driven technical change separately, and while these two driving forces interact in the real world, this does not change the validity of their insights.

In case of R&D driven technical change, most of the lessons of the TAR are confirmed in that the carbon tax has a lower time profile and needs to be set up early to act as a price signal, while real abatement occurs in subsequent periods. What is ambiguous is the net result in terms of welfare costs, since the fact that the carbon tax is lower may be outweighed by crowding out effects on R&D expenditures in other sectors triggered by carbon saving R&D (Smulders 2003). Using empirical estimates on the nature of technical change, Popp (2003) finds that the crowding out is not total and that ignoring induced technical change overstates the welfare costs of an optimal policy by roughly 9 per cent.

In the case of technology modelling that incorporates learning-by-doing (Gerlagh and van der Zwaan, 2004), early abatement is found to be optimal, and, compared to the results of many top-down models, the costs of this strategy is estimated to be low in this study. Consensus for near-term stringent emissions reduction is not absolute however and other studies (Manne and Richels, 2002; Carraro and Galeotti, 2004) conclude that introducing LBD does not drastically change the time profile of abatement. One question that remains to be clarified in a stochastic framework is the extent to which inertia in technical systems may be a more critical factor for the timing of abatement than the specification selected to describe technical change.

3.6.1.6 Timing of action on non-CO_2 gases and on carbon sequestration and their implications for de-carbonisation pathways

An increasing amount of effort has been devoted since the TAR to analysing the policy importance of using options other than decarbonisation of the energy system for achieving climate objectives. In particular; mitigation of non-CO_2 gases; geological carbon storage; and biological carbon storage or sequestration through vegetation and soil management, have been the focus of research. These analyses examine the extent to which it is possible to alleviate the constraint impinging on the energy sector over the short to medium term and to facilitate the transition toward low carbon-intensive development patterns through non-energy mitigation measures. In particular, research effort has focussed on the optimal timing of such options, including whether options should be used in the short term to facilitate transition in the energy system or over longer time horizons as safety-valves as a contingency where ‘bad surprises’ force an accelerated reduction in net emissions. Determining the optimal use of these options requires assessment of the additional social value of these actions at a given point in time and throughout the entirety of a long run climate control program - considerations which are not independent of assumptions about climate risks or de-carbonisation policies.

Models used to study hedging strategies represent the carbon-cycle in a compact manner as if its behaviour was independent from the time profile of GHGs emissions. But a number of contributions have shown that the carbon-cycle is sensitive to this time profile (Cox *et al.*, 2000; Friedlingstein *et al.*, 2001) and deforestation (Gitz et Ciais, 2003). In other words, the estimated temperature in 2100 (and the rate of temperature change in this century) is as much, or more, controlled by the pathway to stabilisation than by the stabilisation target itself (O’Neill & Oppenheimer 2004; Hoegh-Guldberg 1999; Kainuma *et al.* 2004).

3.6.1.6.1 Role of biological and geological carbon sequestration

Since the TAR, much research has focused on the potential for carbon capture and geologic sequestration, revealing that there is significant uncertainty about technical options and their social acceptance. Literature in this area indicates that carbon sequestration lowers the overall cost of reaching emissions targets. Ha-Duong and Keith (2003) show that if carbon capture and storage can be achieved with no leakage over time, the option decreases the need for near-term precautionary abatement. However, Keller (2004) cautions that under the assumption of leakage from geologic sinks, net damages over long time horizons cannot be made independently from assumptions regarding the level of decarbonisation achieved using this option.

Since Kyoto, interest has grown in the use of biological carbon sequestration to partially substitute for fossil fuel emission mitigation to stabilise atmospheric concentrations of CO_2. However, because the cumulative amount of carbon that can be stored in biological ecosystems is limited, a question arises as to the optimal timing of deploying this option. The question of timing arises because significant use of biological sequestration today would place the world on a lower emissions trajectory, while sequestration later may assist in managing an abatement cost peak under circumstances where stringent concentration ceilings and rapid GHG mitigation were required. Kirschbaum (2003) and Gitz *et al.* (2004) examine issues of timing in relation to biological sequestration and find that the social value of transitory biological sequestration is high only under aggressive abatement policy in the energy sector and may be negative under the opposite assumption. They show that sequestration should be mobilised moderately as a ‘brake’ to slow the rate of growth of GHG concentrations and to help achieve the optimal rate of abatement in the energy sector, since this allows arrival at the date of resolution of uncertainty with a high flexibility margin.

Other contributions insist on the asymmetry between carbon emitted by burning fossil energy and carbon emitted (or released) by managing terrestrial ecosystems, because land-cover management not only releases carbon (like fossil fuel burning) but also implies a change in the future dynamic properties of the carbon-cycle. For instance, when croplands replace forests, the residence time of carbon in the biosphere decreases, thereby decreasing the sink capacity of terrestrial ecosystems.

3.6.1.6.2 Role of multi-gas mitigation options

A number of parallel numerical experiments have been carried out by the Energy Modelling Forum on the role of multi-gas mitigation. Although it can be argued that abatement cost curves for these gases rely on only a few preliminary empirical studies, the conclusion that mitigation of these gases can significantly cut the costs of meeting various emissions reduction targets at various points in time is robust.

The most critical question, from a policy point of view, is how to compare the relative contribution of these gases to climate forcing. Criticisms of the use of GW_p as an integrating index are well-established but there is currently no consensus about alternatives that can be easily used in optimal control models to study optimal timing of abatement of these gases. This technical difficulty explains why no study has been published so far in a stochastic optimal control framework in a similar way to studies on CO_2 or biological carbon sequestration. However, theoretical analysis suggests two important conclusions:

i. if the rate of warming in future decades is viewed as a binding constraint (in a cost-effectiveness framework) or as causing significant damages, then abating short-lived gases such as methane would have a high social value over the short run; it would slow down global warming and allow time for dissemination and uptake of low cost carbon saving technologies;
ii. if global warming in future decades is viewed as less critical than possible high climate risks beyond given, currently unknown, concentration thresholds, then it would be economically more efficient to trigger abatements of short-lived gases only after the resolution of information about these climate change risks in order to facilitate the switching towards very tight concentration constraints.

3.6.2 The choice of a near term-hedging strategy in the context of long term climate uncertainty

Given the uncertainty surrounding key socio-economic drivers of emissions, uncertainty about scientific phenomena in relation to long term climate change, and uncertainty surrounding the impact of the aforementioned factors on the timing of climate action, one question for policymakers is how to choose a near term hedging strategy to minimise future adverse impacts from climate change. A related question lies in determining the interaction between mitigation and adaptation, and these issues were discussed in Section 3.5.

In determining a near term hedging strategy, policymakers must determine whether the present emissions trajectory is consistent with long-term emissions/abatement goals, and must therefore consider the possible range of end-points and the sensitivity of this range to near-term decisions.

Economists typically use two approaches to calculating abatement pathways. The first assumes that both the expected and the desired concentration levels are known with certainty, and the issue is in identifying the least-cost abatement pathway for achieving the prescribed target. The second approach recognises that there is significant uncertainty regarding long term emissions objectives, and seeks to identify the optimal near term hedging strategy consistent with risk management.

In the first approach, the choice of pathway can be seen as a GHG budget problem. A concentration target defines the allowable amount of GHG emissions between now and the date at which the target is to be achieved. The issue is how best to allocate this budget over time. The assumption that the target is known with certainty is, of course, an oversimplification. But fortunately, policy makers are not required to make once-and-for-all decisions binding their successors over very long time horizons. There will be ample opportunities for mid-course adjustments over the course of the century.

In light of this reality, climate negotiations are best viewed as an ongoing process of 'act-then-learn'. The UNFCCC recognises the dynamic nature of the decision problem and calls for periodic reviews 'in light of the best scientific information on climate change and its impacts'. Current decision makers must aim at evolving an acceptable hedging strategy - one that balances the risks of acting too aggressively with one of not acting aggressively enough.

The risk premium – the amount that society is willing to pay to avoid risk – is ultimately a political decision that differs among countries. For example, if it is assumed that there is a likelihood of substantial harm, abatement costs are low, and society is highly risk averse, then an aggressive abatement policy would be optimal. Conversely, if it is assumed that the likelihood of great harm is small, abatement costs are high, and society is less risk averse, then a less aggressive abatement policy will be optimal. As uncertainty is resolved over time, the level of abatement may be adjusted.

It is difficult and perhaps counterproductive to explore the payoffs from various types of investments without a conceptual framework for thinking about their interactions. Decision analysis provides one such framework. It allows for the systematic evaluation of near-term options in light of the careful consideration of the potential consequences. The next several decades will require a series of decisions on how best to reduce the risks from climate change. Again, there will no doubt be opportunities for learning and midcourse corrections. The immediate challenge facing policy makers is what actions make sense today in the face of the many long-term uncertainties.

A caricature of the climate policy 'decision tree' is presented in figure 3.6-1. In the parlance of decision analysis, the squares represent points at which decisions are made, the circles represent the reduction of uncertainty and the arrows indicate the wide range of possible decisions and outcomes. In its current manifestation, the first node summarises some of today's investment options - how much should be invested in mitigation, in adaptation, in expanding mitigative and adaptive capacity, or in research to reduce scientific uncertainty? Once an action is taken, there are opportunities to learn and make mid-course corrections. There is no implied meaning to the order of the uncertainty nodes - they are intended to represent some of the types of learning that will occur between now and the next set of decisions. Nor will uncertainty necessarily be fully resolved, but new information may influence future actions. Although the diagram may give the impression that learning and decision making takes place at discrete intervals, the figure is only a caricature: learning and decision making is, of course a continuous process.

[INSERT **Figure 3.34** here]

The decision tree is intended to provide a framework for thinking about the problem in terms of short and long run issues and mitigation/adaptation tradeoffs. Theoretically, with information on the options, outcomes, likelihoods, quality of information, and objectives, one could determine the optimal near-term investment portfolio. Clearly, a comprehensive analysis of all relevant options would be extremely difficult to undertake and require a great deal of skill and care. Nevertheless, this does not mean that the framework cannot be used to explore various aspects of the issue. For example, an issue that needs further exploration at present is the impact of adaptation investments on near-term abatement hedging strategies. That is, what is the impact of lowering the damages from climate change in the future on today's abatement decisions? Such an analysis is required if the synergies and tradeoffs between mitigation and adaptation are to be understood.

Several studies have attempted to identify the optimal near-term hedging strategy taking into account the uncertainty regarding possible long-term objectives. These studies find that the desirable amount of hedging depends on assessment of the expected costs and benefits of climate change.

3.6.2.1 Empirical studies on hedging strategies

Among the many difficulties associated with a long-term stabilisation target in any domain of the climate change process (radiative forcing, concentration, temperature change, tolerable impacts), two stand out prominently: first, uncertainty about the implications of the selected target in other domains (for example, what is the plausible range of temperature change or ecosystem impacts that might be triggered by a given GHG-equivalent concentration target); second, the difficulty of achieving a consensus about the desirable target. With a view to these difficulties, Pershing and Tudela (2003) outline two alternative approaches to progressing towards climate stabilisation: a hedging strategy (fostering near-term actions without focusing on a specific long-term target within a given range) and a near-term action guided by a gradual move toward consensus on an informal target. They quote the TAR WGIII Chapter 10 that concluded that the degree of near-term hedging is sensitive to the date of resolution of uncertainty, inertia in the energy system, and the need to reach the ultimate target at all costs.

These basic insights have not changed since the TAR. In fact, few new analyses have been added to the hedging literature. The sequential decision approach is adopted by Read and Lermit (2004) to study the case when an unacceptable risk of abrupt climate change is revealed by 2020 in the absence of stabilising CO_2 concentrations at a very low level (e.g., 300 ppm). Their analysis suggests that the massive use of bio-energy with carbon storage (yielding negative carbon emissions) might help restore pre-industrial CO_2 levels by the middle of the 21st century.

Game theory has proven to be a useful tool for analysing various properties of possible coalitions in crafting and implementing international climate policy (see also Chapter 10 in TAR WGIII). More recently, dynamic game theoretical models have been used to explore the possible evolution of the international climate regime after Kyoto. In the sequential game discussed by Ciscar and Soria (2002), players optimise their own moves in response to preceding moves made by other players. The authors demonstrate the impossibility of a 'Kyoto forever' policy and concluded that in the case of cooperation (Nash equilibrium), Non-Annex B countries undertake more ambitious emission reductions in the post-Kyoto steps (10 per cent) than Annex B (5 per cent). This is somewhat surprising but the authors note that these results are very sensitive to the assumptions about regional abatement costs and damages.

In addition to the Nash equilibrium, Forgo *et al.* (2005) use other solution concepts to explore the dynamics of global climate policy when the two large players (Annex-B and Non-Annex B) optimise their own strategies depending on the strategy pursued by the other party in the preceding step. A path starting with a partial compliance with the Kyoto Protocol, followed by ambitious mitigation strategies in the post-Kyoto period and easing off in the subsequent period by one player (preferably non-Annex B) seems to be stable and plays a characteristic role in the correlated equilibrium (combining stability with global optimality) and in the cooperative solution as well.

Climate change falls in the category of stock externalities and its mitigation requires long-term commitment. However, alliances that are feasible at the beginning might be influenced by unexpected shocks that affect their coalition commitments. In an effort to step beyond the inadequacy of the so-called open-loop solutions under these circumstances, Yang (2003) develops a modelling approach to produce closed-loop strategies that are suitable for analysing cases when re-evaluation or re-negotiation of coalitions might arise. These strategies tend to deviate from the open-loop strategies and may not preserve the incentive compatibility of the initial bargaining. They are secure with respect to re-negotiation if one region's damages turn out to be too high or its mitigation costs too low. Moreover, free riding always impedes coalitions.

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