Chapter 3  
Issues related to mitigation in the long-term context

Warning: This chapter needs to be read in conjunction with the list of accepted changes in the underlying report (Document IPCC WGIII: 9th/Doc 3 (4.V.20007), available from the Working Group III website (www.mnp.nl/ipcc/index.html).
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Coordinating Lead Authors
Brian Fisher (Australia), Nebojsa Nakicenovic (Austria/Montenegro)

Lead Authors
Knut Alfsen (Norway), Jan Corfee Morlot (France/USA), Francisco de la Chesnaye (USA), Jean-Charles Hourcade (France), Kejun Jiang (China), Mikiko Kainuma (Japan), Emilio La Rovere (Brazil), Anna Matysek (Australia), Ashish Rana (India), Keywan Riahi (Austria), Richard Richels (USA), Steven Rose (USA), Detlef Van Vuuren (The Netherlands), Rachel Warren (UK)

Contributing Authors
Phillipe Ambrosi (France), Fatih Birol (Turkey), Daniel Bouille (Argentina), Christa Clapp (USA), Bas Eickhout (The Netherlands), Tatsuya Hanaoka (Japan) Yuzuru Matsuoko (Japan), Brian O’Neill (USA), Hugh Pitcher (USA), Shilpa Rao (India), Ferenc Toth (Hungary)

Review Editors
John Weyant (USA), Mustafa Babiker (Kuwait)
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EXECUTIVE SUMMARY

This chapter documents 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 during the past five years. Of special relevance is how ranges published for driving forces and emissions in the newer literature compare with those used in TAR, SRES and pre-SRES scenarios. An important focus of the chapter is on scenarios that stabilize atmospheric concentrations of GHG. New multigas stabilization scenarios represent a significant change in the new literature compared to TAR that focused mostly on CO\textsubscript{2} emissions. They also explore lower levels and a wider range of stabilization than in TAR.

The main finding from the comparison of SRES and new scenarios in the literature is that the ranges of main driving forces and emissions have not changed very much (high agreement, much evidence). Overall, the ranges of emissions from scenarios reported before and after SRES without climate policy have not changed appreciably. Some changes are noted for population and economic growth assumptions. Population scenarios from major demographic institutions are lower than they were at the time of TAR, but they have not been fully implemented so far in the emissions scenarios in the literature. All other factors being equal, lower population projections are likely to result in lower emissions. However, in the scenarios that used lower projections, changes in other drivers of emissions have offset their impact. Regional medium-term (2030) economic projections for some developing country regions are currently lower than the highest scenarios used in TAR. Otherwise, economic growth perspectives have not changed much even though they are among the most intensely debated aspects of the SRES scenarios. In terms of emissions, the most noticeable changes occurred for projections of SO\textsubscript{x} and NO\textsubscript{x} emissions. As short-term trends have moved down, the range of projections for both is currently lower than the range published before TAR. A small number of new scenarios have begun to explore emission pathways for black and organic carbon.

Baseline land-related CO\textsubscript{2} and non-CO\textsubscript{2} GHG emissions remain significant with continued but slowing land conversion and increased use of high-emitting agricultural intensification practices due to rising global food demand and shifts in dietary preferences towards meat consumption. The post-SRES scenarios suggest a degree of expert agreement that the decline in annual land use change carbon emissions over time will be less dramatic (slower) than suggested by many of the SRES scenarios. Global long-term land-use scenarios are scarce in numbers but growing, with the majority of the new literature since SRES contributing new forestry and biomass scenarios. However, the explicit modeling of land-use in long-term global scenarios is still relatively immature with significant opportunities for improvement.

In the debate of the use of exchange rates, market exchange rates (MER) or purchasing power parities (PPP), evidence from the limited number of new PPP-based studies indicates that the choice of metric for GDP (MER or PPP) does not appreciably affect the projected emissions, when metrics are used consistently. The differences, if any, are small compared to the uncertainties caused by assumptions on other parameters, e.g. technological change (high agreement, medium evidence).

The numerical expression of GDP clearly is dependent on conversion measures; thus GDP expressed in PPP will deviate from GDP expressed in MER, more so for developing countries. The choice of conversion factor (MER or PPP) depends on the type of analysis or comparison being undertaken. However, when it comes to calculating emissions (or other physical measures like energy), the choice between MER or PPP based representations of GDP should not matter, since emission
intensities will change (in a compensating manner) when the GDP numbers change. Thus, if a consistent set of metrics is employed, the choice of metric should not appreciably affect the final emission level (*high agreement, medium evidence*). This supports the SRES in the sense that the use of MER or PPP does not in itself lead to significantly different emission projections outside the range of the literature (*high agreement, much evidence*). In case of SRES, the emissions trajectories were the same whether economic activities in the four scenario families were measured in MER or PPP.

Some studies find differences in emission levels between using PPP and MER based estimates. These results critically depend on, among other things, convergence assumptions (*high agreement, medium evidence*). In some of the short-term scenarios (with a horizon to 2030) a bottom up approach is taken where assumptions about productivity growth and investment and saving decisions are the main drivers of growth in the models. In long-term scenario models, a top down approach is more commonly used where the actual growth rates are more directly prescribed based on convergence or other assumptions about long-term growth potentials. Different results can also be due to inconsistencies in adjusting the metrics of energy efficiency improvement when moving from MER to PPP based calculations.

There is a clear and strong correlation between the CO₂-equivalent concentrations (or radiative forcing) of the published studies and the CO₂ only concentrations by 2100, because CO₂ is the most important contributor to radiative forcing. Based on this relationship, to facilitate scenario comparison and assessment, stabilization scenarios (both multigas and CO₂ only studies) have been grouped in this chapter into different categories that vary in the stringency of the targets from low to high radiative forcing, CO₂-equivalent concentrations and CO₂ only concentrations by 2100, respectively.

Essentially, any specific concentration or radiative forcing target, from the lowest to the highest, requires emissions to eventually fall to very low levels as the removal processes of the ocean and terrestrial systems saturate. For low to medium targets, this would need to occur this century but higher stabilization targets can push back the timing of such reductions to beyond 2100. However, to reach a given stabilization target, emissions must ultimately be reduced well below current levels. For achievement of the very low stabilization targets from many high baseline scenarios, negative net emissions are required toward the end of the century (*high agreement, much evidence*).

The timing of emission reductions depends on the stringency of the stabilization target. Lowest stabilization targets require an earlier peak of CO₂ and CO₂-equivalent emissions. In the majority of the scenarios in the most stringent stabilisation category (a stabilization level below 490 ppmv CO₂-equivalent), emissions are required to decline before 2015 and are further reduced to less than 50% of today’s emissions by 2050. For somewhat higher stabilization levels (e.g., a stabilization level below 590 ppmv CO₂-equivalent) global emissions in the scenarios peak generally around 2010 – 2030, followed by a return to 2000 levels on average around 2040. For high (e.g., a stabilization level below 710 ppmv CO₂-eq) the median emissions peak around 2040 (*high agreement, much evidence*).

Long-term stabilization scenarios highlight the importance of technology improvements, advanced technologies, learning-by-doing, and induced technological change both for achieving the stabilization targets as well as cost reduction (*high agreement, much evidence*). While the technology improvement and use of advanced technologies have been employed in scenarios largely exogenously in most of the literature, new literature covers learning-by-doing and endogenous technological change. The latter show results to be different by the ways of deployment of technologies while maintaining their key role in achieving stabilization and reduction of cost.
Decarbonization trends are persistent in majority of intervention and non-intervention scenarios (high agreement, much evidence). The medians of scenario sets indicate decarbonization rates of about 0.9 (pre-TAR) and 0.6 (post-TAR) compared to historical rates of about 0.3 % per year. On the upper end of the range decarbonization rates of up to 2.5 % per year are observed in more stringent stabilization scenarios, where complete transition away from carbon intensive fuels is considered.

The scenarios that report quantitative results with drastic CO$_2$ reduction targets of 60-80% in 2050 (compared to today’s emission levels) require an increase in the rates of improvement of energy intensity and carbon intensity by two to three times their historical levels. This is found to require different sets of mitigation options across regions with varying shares of nuclear energy, CCS, hydrogen, and biomass.

The costs of stabilization crucially depend on the choice of the baseline, related technological change and resulting baseline emissions; stabilization target and level; and the portfolio of technologies considered (high agreement, much evidence). Additional factors include assumptions with regard to the use of flexible instruments and with respect to revenue recycling. Some literature identifies low-cost technology clusters allowing for endogenous technological learning with uncertainty. This suggests that a decarbonised economy may not cost any more than a carbon-intensive one, if technological learning is taken into account.

There are different metrics for reporting costs of emissions reductions although most models report them in macro-economic indicators-in particular GDP losses. For stabilization at 4-5 W/m$^2$ (or ~590-750 ppmv CO$_2$-eq) macro-economic costs range from -1 to 2% of GDP below baseline in 2050. For a more stringent target of 3.5 - 4.0 W/m$^2$ (~535-590 ppm CO$_2$-eq) the costs range from slightly negative to 4% GDP loss.

Multigas emissions reduction scenarios are able to meet climate targets at substantially lower costs compared to CO$_2$-only strategies (for the same targets, high agreement, much evidence). Inclusion of non-CO$_2$ gases provides a more diversified approach that offers greater flexibility in the timing of the reduction program.

Including land-use mitigation options as abatement strategies provides greater flexibility and cost-effectiveness for achieving stabilisation (high agreement, medium evidence). Even if land activities are not considered as mitigation alternatives by policy, consideration of land (land-use and land cover) is crucial in climate stabilization for its significant atmospheric inputs & withdrawals (emissions, sequestration, and albedo). Recent stabilisation studies indicate that land-use mitigation options could provide 15 to 40% of total cumulative abatement over the century. Agriculture and forestry mitigation options are projected to be cost-effective abatement strategies across the entire century. In some scenarios, increased commercial biomass energy (solid and liquid fuel) is a significant abatement strategy, providing 5 to 30% of cumulative abatement and potentially 1 to 15% of total primary energy over the century.

Long-term mitigation policy and decision making in a risk management framework is informed by concern about climate change impacts and integrated assessments. These consider the relationship between key vulnerabilities to predicted climate impacts, adaptation potentials as well as the costs of emissions reductions. In particular they are informed by the (physical and monetized) benefits of avoided climate change damages for any given set of policies.

Decision making about the appropriate level of mitigation in a cost-benefit context is an iterative risk management process considering investment in mitigation and adaptation, co-benefits of under-
taking climate change decisions and the damages due to climate change. It is intertwined with development decisions and pathways. Cost-benefit analysis tries to quantify climate change damages in monetary terms (as social cost of carbon - SCC - or time-discounted damages). Due to large uncertainties and difficulties in quantifying non-market damages, it is difficult to estimate SCC with confidence. Results depend on a large number of normative and empirical assumptions that are not known with any certainty. SCC estimates in the literature vary by three orders of magnitude, are likely to be understated and will increase a few percent per year (i.e. 2.4% for carbon only and 2-4% for the social costs of other greenhouse gases (WGII, Ch 20). Comparing SCC estimates with carbon prices corresponding to stabilisation scenarios shows that SCC is at least comparable to, and possibly higher than, carbon prices for even the most stringent scenarios assessed in this report. Or, in other words, costs of stabilisation tend to be comparable to or lower than costs of inaction (high agreement, limited evidence).

For any given stabilisation pathway, a higher climate sensitivity raises the probability of exceeding temperature thresholds for key vulnerabilities (high agreement, much evidence). For example, policymakers may want to use the highest values of climate sensitivity (i.e. 4.5°C) within the ‘likely’ range of 2-4.5°C set out by Working Group I (Ch 10) to guide decisions, which would mean that achieving a target of 2°C (above the pre-industrial level), at equilibrium, is already outside the range of scenarios considered in this chapter, whilst a target of 3°C (above the pre-industrial level) would imply stringent mitigation scenarios with emissions peaking within 10 years. Using the ‘best estimate’ assumption of climate sensitivity, the most stringent scenarios (stabilising at 435-490 ppmv CO₂-eq) could limit global mean temperature increases to 2-2.4°C above the pre-industrial level, at equilibrium, requiring emissions to peak within 15 years and to be around 50% of current levels by 2050. Scenarios stabilising at 535-590 ppmv CO₂-eq could limit the increase to 2.8-3.2°C above the pre-industrial level, and those at 590-710 CO₂-eq to 3.2-4°C, requiring emissions to peak within the next 25 and 55 years respectively (high agreement, medium evidence).

Decisions to delay emission reductions seriously constrain opportunities to achieve low stabilisation targets (e.g. stabilising concentrations from 440 to 535 ppmv CO₂-eq), and raise the risk of progressively more severe climate change impacts and key vulnerabilities occurring. For example, if the time when global emissions peak is postponed beyond the next 15 years category, constraining global temperature rise to below 2.6°C above the pre-industrial level (2.0°C above 1990), at equilibrium, would be out of reach using ‘best estimate’ assumptions of climate sensitivity. Once this temperature threshold is breached, climate impacts accrue significantly in the earth and human system.

The risk of climate feedbacks is generally not included in the above analysis but doing so could increase the levels of warming associated with a given atmospheric concentration of greenhouse gases; and hence imply that more stringent mitigation would be required to comply with a given temperature constraint than would otherwise be the case.

Near term mitigation and adaptation decisions are related to long term climate goals (high agreement, much evidence). A risk management or “hedging” approach can assist policy-makers to advance mitigation decisions in the absence of a long term target and in the face of large uncertainties related to the cost of mitigation, the efficacy of adaptation and the negative impacts of climate change. The extent and the timing of the desirable hedging strategy will depend on the stakes, the odds and societies’ attitudes to risks, for example with respect to risks of abrupt change in geophysical systems and other key vulnerabilities. A variety of integrated assessment approaches exist to assess mitigation benefits in the context of policy decisions related to such long term climate goals. There will be ample opportunity for learning and mid-course corrections as new information becomes available. However, actions in the short term will to a large extent determine what future
climate change impacts can be avoided. Hence, analysis of near-term decisions should not be de-
coupled from analysis that considers long-term climate change outcomes (high agreement, much
evidence).
3.1 Emissions scenarios

The evolution of future greenhouse gas emissions and their underlying driving forces is highly uncertain, as reflected in the wide range of future emissions pathways across (more than 750) emission scenarios in the literature. This chapter assesses this literature focusing especially on new multigas baseline scenarios since the publication of the IPCC Special Report on Emissions Scenarios (SRES) (Nakicenovic et al., 2000) and on new multigas mitigation scenarios since the publication of the IPCC Third Assessment Report (TAR Working Group III, Ch. 2, Morita et al., 2001). This literature is referred to as ‘post-SRES’ scenarios.

The SRES scenarios were representative of some 500 emissions scenarios in the literature, grouped as A1, A2, B1 and B2, at the time of their publication in 2000. Of special relevance in this review is how representative the SRES ranges of driving forces and emission levels are of the newer scenarios in the literature and how representative are the TAR stabilization levels and mitigation options compared with the new multigas stabilization scenarios. Other important aspects of this review include methodological, data and other advances since the time the SRES scenarios were developed.

This chapter uses the results of the Energy Modeling Forum (EMF-21) scenarios and the new Innovation Modelling Comparison Project (IMCP) network scenarios. In contrast to SRES and post-SRES scenarios, these new modelling comparison activities are not based on fully harmonized baseline scenario assumptions but rather on ‘modeller’s choice’ scenarios. Thus, further uncertainties have been introduced due both to different assumptions and different modelling approaches. Another emerging complication is that even baseline (also called reference) scenarios include some explicit policies directed at emissions reduction, notably due to the Kyoto Protocol entering into force, and other climate-related policies that are being implemented in many parts of the world.

Another difficulty in straightforward comparisons is that the information and documentation of the scenarios in the literature varies considerably.

3.1.1 The definition and purpose of scenarios

Scenarios describe possible future developments. They can be used in an exploratory manner or for a scientific assessment in order to understand the functioning of an investigated system (Carpenter et al., 2005).

In the context of the IPCC assessments, scenarios are directed at exploring possible future emissions pathways, 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 purposes of emissions scenarios (Alcamo et al., 1995):

- 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; and
- To provide input to negotiations of possible agreements to reduce GHG emissions.
Scenario definitions in the literature differ depending on the purpose of the scenarios and how they were developed. The SRES report (Nakicenovic et al., 2000) defines a scenario as a plausible description of how the 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 change or prices). 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 at 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 density 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 population (Lutz et al., 2001) and CO$_2$ emissions (Webster et al., 2002, 2003; O’Neill, 2004).

3.1.1.1 Types of scenarios

The scenario literature can be split into two largely non-overlapping streams - quantitative modelling and qualitative narratives (Morita et al., 2001). 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 (Raskin et al., 2005). It is particularly noteworthy that recent developments in scenario analysis are beginning to bridge this difficult gap (Nakicenovic et al., 2000; Morita et al. 2001 and Carpenter et al., 2005).

3.1.1.2 Narrative storylines and modelling

The literature based on narrative storylines that describe futures is rich going back to the first global studies of the 1970s (e.g. Kahn et al., 1976; Kahn and Weiner 1967) and is also well represented in more recent literature (e.g. Peterson, 1994; Gallopin et al. 1997; Raskin et al., 1998; Glenn and Gordon, 1997). Well known are the Shell scenarios that are principally based on narrative stories with illustrative quantification of salient driving forces and scenario outcomes (Wack 1985a, b; Schwartz, 1992; Shell, 2005).

Catastrophic futures feature prominently in the narrative scenarios literature. They typically involve large-scale environmental or economic collapse, extrapolating current unfavourable conditions and trends in many regions. 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. This report does not analyze such futures except cases that do provide emissions pathways.

3.1.1.3 Global futures scenarios

Global futures scenarios are deeply rooted in the long history of narrative scenarios (Millenium Ecosystems Assessment, 2005; UNEP, 2002). The direct antecedents of contemporary scenarios lie with the future studies of the 1970s (Raskin 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.,

1 Prominent examples of such scenarios include the ‘Retrenchment’ (Kinsman, 1990), the ‘Dark Side of the Market World’ or ‘Change without Progress’ (Schwartz, 1991), the ‘Barbarization’ (Gallopin et al., 1997) and ‘A Passive Mean World’ (Glenn and Gordon, 1997).
1976). At this time, scenario analysis was first used at Royal Dutch/Shell as a strategic management technique (Wack, 1985a, b; Schwartz, 1992).

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; 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, starting from 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 (Raskin et al., 2005).

### 3.1.2 Introduction to mitigation and stabilization scenario

Climate change intervention, control, or mitigation scenarios capture measures and policies for reducing GHG emissions with respect to some baseline (or reference) scenario. They contain emission profiles as well as costs associated with the emissions reduction but often do not quantify the benefits of reduced impacts from climate change. Stabilization scenarios are mitigation scenarios that aim at a pre-specified GHG reduction pathway, leading to stabilization of GHG concentrations in the atmosphere.

For the purposes of this chapter, a scenario is identified as a mitigation or intervention scenario if it meets one of the following two conditions:

- incorporates specific climate change targets, which may include absolute or relative GHG limits, GHG concentration levels (e.g., CO₂ or CO₂-equivalent stabilization scenarios), or maximum allowable changes in temperature or sea level;
- includes explicit or implicit policies and/or measures of which the primary goal is to reduce CO₂ or a broader range of GHG emissions (e.g., a carbon tax, carbon cap or a policy encouraging the use of renewable energy).

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

Another type of mitigation (intervention or climate policy) scenario approach specifies future ‘worlds’ that are internally consistent with some specified climate target (e.g., a global temperature increase of no more than 1°C by 2100), and then works 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 (Morita et al., 2001). A number of such new multigas stabilization scenarios are assessed in this chapter.

Confusion can arise when the inclusion of ‘non-climate-related’ policies in a reference (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 non-intervention scenario. Such a 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 (so-called multiple benefits). Whether such policies are assumed to be adopted for climate or non-climate policy related reasons 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 scenario generation is the nature of the economic development process and whether and to what extent developing countries will follow the development pathways of industrialized countries with respect to energy use and GHG emissions. The ‘lock-in’ effects of infrastructure, technology and product design choices made by industrialized countries in the post-world war II period of low energy prices are responsible for the major recent increase in world GHG emissions. A simple mimicking by developing countries of the development paradigm established by industrialized countries could lead to a very large increase of global GHG emissions (see Ch. 2).

It may be noted, however, that Energy/GDP elasticities in industrialized countries have first increased in successive stages of industrialization, with acceleration during the fifties and sixties, but have sharply decreased since then, due to factors such as relative growth of services in GDP share, technical progress induced by higher oil prices and energy conservation efforts.

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 industrial policies directed toward rural development and integrated urban, regional, and transportation planning, thereby avoiding urban sprawl and facilitating more efficient transportation and energy systems. The main issue is the magnitude and viability to tap the potential for technological ‘leapfrogging’ whereby developing countries can bypass emissions-intensive intermediate technology and jump straight to cleaner technologies. There are 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). Section 12.2 of chapter 12 will further develop this argument.

On the other hand, the barriers to such development pathways should not be underestimated, going from financial constraints to cultural behaviours in industrialized as in developing countries, including the lack of appropriate institution 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).

### 3.1.4 Economic growth and convergence

Determinants of long-term GDP per person are labour force and its productivity projections. Labour force utilization depends on factors such as number of people of working-age, the level of structural unemployment and hours worked per worker. Demographic change is still the major determinant of the baseline labour supply (Martins and Nicoletti, 2005). Long-term projections of labour productivity primarily depend on improvements in labour quality (capacity building) and the pace of technical change associated with building up the capital-output ratio and the quality of capital.

The literature 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) suggests that economic ‘catch-up’ and convergence strongly depend on 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).

The economic convergence literature (Abramovitz, 1986; Baumol, 1986) using a standard neoclassical economic growth setup following Solow (1956) found evidence of convergence only between the richest countries. Other research efforts documented ‘conditional convergence’, meaning that countries appeared to reach their own steady states at a fairly uniform rate of two per year (Barro, 1991; Mankiw et al., 1992). Jones (1997) found that the future steady-state distribution of per person 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 past trends. Total factor productivity (TFP) levels and convergence for the evolution of income distribution are also important. Expected catch-up, and even overtaking in per person incomes, as well as changes in leaders in the world distribution of income are among some of the findings in this literature. Quah (1993, 1996) found that the world is moving toward a bimodal income distribution. Some recent assessments demonstrate divergence, not convergence (World Bank, 2002; Halloy et al., 2005; UN-SD, 2005).

Convergence is limited for 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. Social inertia (as referred to in chapter 2, see 2.3.3) also contributes to delay convergence. Therefore only limited catch-up can be factored in baseline 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 accelerate the adoption of new technologies and create incentives for human capital formation and thus accelerate convergence (Martins and Nicoletti, 2005). Nelson and Fagerberg, arguing within an evolutionary paradigm, have different perspectives on the convergence issue (Fagerberg, 1995; Fagerberg et al., 2005; UNIDO, 2005). It should be acknowledged that the old theoretical controversy about steady-state economics and limits to growth still continues (Georgescu-Roegen, 1971).

The above discussion provides the economic background for the range of assumptions on the long-term convergence of income between developing and developed countries (measured by GDP per person) found in the scenario literature. The annual rate of income convergence between 11 world regions in the SRES scenarios falls within the range of less than 0.5% in the A2 scenario family to less than 2.0% in A1 (both in purchasing power parity and market exchange rate metrics). The
highest rate of income convergence in SRES is similar to the observed convergence in the period 1950-1990 of 90 regions in Europe (Barro and Sala I Martin, 1997). However, Gruebler et al. (2006) note that extending convergence analysis to national or subnational level would suggest that income disparities are larger than suggested by simple inter-regional comparisons and that scenarios of (relative) income convergence are highly sensitive to the spatial level of aggregation used in the analysis. An important finding from the sensitivity analysis performed is that less convergence generally yields higher emissions (Riahi, 2005). In B2, an income ratio (between 11 world regions, in market exchange rates) of 7 corresponds to CO₂ emissions of 14.2 GtC in 2100, while shifting this income ratio to 16 would lead to CO₂ 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 pathways and GHG emissions

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 to determine the main factors that will ultimately influence the amount of GHG emissions, given an assumed overall rate of economic growth (Jung et al., 2000; see also examples discussed in section 12.2 of chapter 12):

- structural changes in the production system, namely the role of high or low energy-intensive industries and services;
- technological patterns in sectors such as energy, transportation, building, waste, agriculture and forestry - the treatment of technology in economic models has received much attention and triggered the most difficult debates within the scientific community working in this field (Edmonds and Clarke, 2005; Grubb et al., 2005; Shukla, 2005; Worrell, 2005; Köhler et al., 2006);
- geographical distribution of activities encompassing both human settlements and urban structures in a given territory, and its twofold impact on the evolution of land use, 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 person, 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; and
- 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 person 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 household budget; and the share of energy and transportation costs in total costs in the industrial sector.

These parameters remain important, but the outcome in terms of GHG emissions will also depend on dynamic linkages between technology, consumption patterns, transportation and urban infrastructure, urban planning, and rural-urban distribution of population (see also Ch. 2 and 11 for a more extensive discussion of some of these issues).

3.1.6 Institutional frameworks

Recent research has included studies on the role of institutions as a critical component in an economy’s capacity to use resources optimally (Ostrom 1990; Ostrom et al., 2002) and 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). Institutional structures vary considerably across nations even with similar levels of economic development. 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’ (World Bank, 1992, Beierle and Cayford, 2002; Ostrom et al., 2002; Rydin, 2003). Other relevant developments may include greater use of market mechanisms and institutions to enhance global cooperation and more effectively manage global environmental issues (see also Ch. 12).

A weak institutional structure basically explains why an economy can be in a position that is significantly below the theoretically efficient production frontier, with several economists terming it as a ‘missing link’ in the production function (Meier, 2001). Furthermore, weak institutions also cause frictions in economic exchange processes resulting in high transaction costs.

The existence of weak institutions in developing countries has implications for the capacity to adapt to or mitigate 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 in society, and the interaction between them (Ch. 2 and 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 (Halsnæs, 2002, see also Ch.2 and 12).

In the presently less industrialized regions, there is a large and relatively unskilled part of the population that is not yet involved in the formal economy. In many regions industrialization leads to wage differentials that draw these people into the more productive, formal economy, causing accelerated urbanization in the process. 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 shape institutions and how they function. Social norms of ownership and distribution have a vital influence on the structure of production and consumption as well as the quality and extent of the social ‘infrastructure’ sectors, such as education, which are paramount to capacity building and technological progress. Unlike institutions, social and culture processes are often more inflexible and difficult to influence. However, specific sectors such as education are amenable to interventions. Barring some negative features, such as segregation, 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 infrastructure that underpins technological progress and human welfare (Jung et al., 2000) as well as evolving perceptions and social understanding of climate change risk (see Rayner and Malone, 1998; Douglas and Wildavsky, 1982; Slovic, 2000).

While institutional arrangements are sometimes described as part of storylines, scenario specifications generally do not include explicit assumptions about them. The role of institutions in the implementation of development choices and its implications to climate change mitigation will be further discussed in section 12.2 of chapter 12.

### 3.2 Baseline scenarios

#### 3.2.1 Drivers of emissions

Trajectories of future emissions are determined by complex dynamic processes that are influenced by factors such as demographic and socio-economic development, and technological and institutional change. An often used identity to describe changes in some of these factors is based on the IPAT identity (Impact = Population × Affluence × Technology – see Holdren, 2000; Ehrlich and Holdren, 1971) and in emissions modelling is often called the Kaya identity (see section 3.2.1.4 and Yamaji et al., 1991). These two relationships state that energy-related emissions are a function of population growth, GDP per person, changes in energy intensity, and carbon intensity of energy consumption. These factors are discussed in Section 3.2.1 to describe new information published on baseline scenarios since the TAR. There are more than 800 emission scenarios in the literature including almost 400 baseline (non-intervention) scenarios. Many of these scenarios were collected during the IPCC SRES and TAR processes (Morita & Lee, 1998a) and made available through the Internet. 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 (Nakicenovic et al., 2006; Hanaoka et al., 2006). The recent scenario literature is discussed and compared with the earlier scenarios in this section.

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2 It should be noted that the sources of scenario data vary. For some scenarios the data come directly from the modelling teams. In other cases they have been assembled from the literature or from other scenario comparison exercises such as EMF-19, EMF-21, and IMCP. For this assessment the scenario databases from Nakicenovic et al. (2006) and Hanaoka et al., (2006) were updated with most recent information. The scenarios published before the year 2000 were retrieved from the database during SRES and TAR. The databases from Nakicenovic et al. (2006) and Hanaoka et al., (2006) can be accessed on the following web-pages: http://iiasa.ac.at/Research/TNT/WEB/scenario_data-base.html and http://www-cger.nies.go.jp/scenario.
3.2.1.1  Population projections

Current population projections reflect less global population growth than was expected at the time the TAR was published. Since the early 1990s demographers have revised their outlook on future population downward, based mainly on new data indicating that birth rates in many parts of the world have fallen sharply.

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, 2006). This global result is driven primarily by changes in outlook for the Asia and the Africa-Latin America-Middle East (ALM) region. On a more detailed level, trends are driven by changes in the outlook for Sub-Saharan Africa, the Middle East and North Africa region, and the East Asia region, where recent data show lower than expected fertility rates 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. This comes from 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 Eastern Europe and Central Asia (Reforming economic, REF) region, projections have been revised downward, especially by the UN, driven mainly by recent data showing very low fertility levels and mortality that are quite high relative to other industrialised countries.

Lutz et al. (2004), UN (2004) and Fisher et al. (in press) have produced updated projections for the world that extend to 2100. The most recent central projections for global population are 1.4 to 2.0 billion (13 to 19%) lower than the medium population scenario of 10.4 billion used in the SRES B2 scenarios. 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.

Most of the SRES scenarios still fall within the plausible range of population outcomes according to more recent literature (see Figure 3.1). However, the high end of the SRES population range now falls above the range of 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 (van Vuuren and O’Neill, 2006). In addition, the population assumptions in SRES and the vast majority of more recent emissions scenarios do not cover the low end of the current range of population projections well. New scenario exercise will need to take the lower population projections into account. All other factors being equal, lower population projections are likely to result in lower emissions. However, a small number of recent studies that have used updated and lower population projections (Carpenter et al., 2005; Van Vuuren et al., 2007; Riahi et al., 2006) indicate that changes in other drivers of emissions might partly offset the impact of lower population assumptions, thus leading to no significant changes in emissions.
Figure 3.1: Comparison of population assumptions in post-SRES emissions scenarios with those used in previous scenarios. Blue shaded areas spans range of 84 population scenarios used in SRES or pre-SRES emissions scenarios; individual curves show population assumptions in 117 emissions scenarios in the literature since 2000. Two vertical bars on the right extend from the minimum to maximum of the distribution of scenarios by 2100. The horizontal bars indicate the 5th, 25th, 50th, 75th and the 95th percentiles of the distributions.

Data source: After Nakicenovic et al., 2006

3.2.1.2 Economic development

Economic activity is a dominant driver of energy demand and thus of emissions of greenhouse gases. This activity is usually reported as gross domestic product (GDP) often measured in per person terms. To derive meaningful comparisons over time, changes in price levels must be taken into account and corrected by reporting activities in constant prices taken from a base year. One way of reducing the effects of different base years employed across various studies is to report real growth rates for changes in economic output. Therefore, the focus below is on real growth rates rather than on absolute numbers.

Given that countries and regions use particular currencies, another difficulty arises in aggregating and comparing economic output across countries and world regions. There are two main approaches: using an observed market exchange rate (MER) in a fixed year or using a purchasing power parity rate (PPP) (see Box 3.1). GDP trajectories in the large majority of long-term scenarios in the literature are calibrated in MER. A few dozen scenarios exist in that use PPP exchange rates, but most of them are shorter-term, generally running out to 2030.

3.2.1.3 GDP growth rates in the new literature

Many of the long-term economic projections in the literature have been specifically developed for climate related scenario work. Figure 3.2 compares the global GDP range of 153 baseline scenarios from the pre-SRES and SRES literature with 130 new scenarios developed since SRES (post-
SRES). There is a considerable overlap in the GDP numbers published, with a slight shift downwards of the median of the new scenarios by about 7% compared to the median in the pre-SRES scenario literature. The data suggests no appreciable change in the distribution of GDP projections.

A comparison of some recent shorter-term global GDP projections with the SRES scenarios is illustrated in Figure 3.3. The SRES scenarios project a very wide range of global economic per person growth rates from 1.0% (A2) to 3.1% (A1) to 2030, both based on MER. This range is somewhat wider than the range covered by the DOE (2005) high and low scenarios (1.2 to 2.5%). The central projections of DOE, IEA and the World Bank all contain growth rates of around 1.5 to 1.9%, thus occurring in the middle of the range of the SRES scenarios. Other medium term energy scenarios are also reported to have growth rates in this range (IEA, 2004).

Regionally, for the OECD and Eastern Europe and Central Asia (Reforming economic, 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 are just above that in recent studies. The differences between the SRES outcomes and more recent projections are largest in the ALM region covering Africa, Latin America and the Middle East. Here, the A1 and B1 scenarios clearly lie above the upper end of the range of current projections (4 to 5%), while A2 and B2 fall near the centre of the range (1.4 to 1.7%). The recent short-term projections reported here contain an assumption that current barriers to economic growth in these regions will slow growth, at least until 2015.

**Figure 3.2**: Comparison of GDP projections in post-SRES emissions scenarios with those used in previous scenarios. The median of the new scenarios is about 7 percent below the median of the pre-SRES and SRES scenario literature. Two vertical bars on the right extend from the minimum to maximum of the distribution of scenarios by 2100. The horizontal bars indicate the 5th, 25th, 50th, 75th and the 95th percentiles of the distributions.
3.2.1.4 The use of MER in economic and emissions scenarios modelling

Recently, the uses of MER-based economic projections in SRES have been criticized (Castles and Henderson, 2003a,b; Henderson, 2004). The vast majority of scenarios published in the literature use MER based economic projections. Some exceptions exist, e.g., MESSAGE in SRES and more recent scenarios with the MERGE model (Manne and Richels, 2003) along with shorter term scenarios to 2030 including the G-Cubed model (McKibbin et al., 2004a, b), the International Energy Outlook (USDOE, 2004), the IEA World Energy Outlook (IEA, 2004) and the POLES model used by the European Commission (2003a). The main criticism of the MER-based models is that GDP data for world regions are not corrected with respect to purchasing power parities (PPP) in most of the model runs. The implied 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 high growth SRES scenarios (A1 and B1 families) assume that regions tend to conditionally converge in terms of relative per person income across regions (see Section 3.1.4). According to the critics, the use of MER together with the assumption of conditional convergence lead to overstated economic growth in the poorer regions and excessive growth in energy demand and emission levels.

![Graph showing global GDP growth per person in SRES scenarios and more recent projections.](image)

**Figure 3.3**: Comparison of global GDP growth per person in the SRES scenarios and more recent projections.


A team of SRES researchers responded to this criticism indicating that the use of MER or PPP data does not in itself lead to different emission projections outside the range of the literature. In addition, they stated that the use of PPP data in most scenarios models was and still is infeasible due to lack of required data in PPP terms, e.g., price elasticities and social accounting matrices (Nakicenovic et al., 2003, Grübler et al., 2004). Also a growing number of other researchers have indicated different opinions on this issue or explored it in a more quantitative sense (e.g., Dixon and Rimmer, 2005; Nordhaus, 2006; Manne and Richels, 2003; McKibben et al., 2004a,b; Holtsmark and Alfsen, 2004a,b; and van Vuuren and Alfsen, 2006).

There are at least three strands to this debate. The first is 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 and robust. The second is whether the choice of the exchange rate matters when it comes to emission scenarios. The third is whether it is possible or practical to develop robust scenarios given the sparseness of relevant and required PPP data. While the GDP data are available in PPP, other economic scenario characteristics such as capital and operational cost of energy facilities are usually available either in domestic currencies of MER. Full model calibration in PPP for regional and global models is still difficult due to the lack of underlying data. This
could be one of the reasons why a vast majority of long-term emissions scenarios continues to be calibrated in MER.

**Box 3.1 Market Exchange Rates and Purchasing Power Parity**

To aggregate or compare economic output from various countries, GDP data must be converted into a common unit. The conversion can be based on observed market exchange (MER) rates or purchasing power parity (PPP) rates where in the latter a correction is made for differences in price levels between countries. The PPP approach is considered to be the better alternative if data are used for welfare or income comparisons across countries or regions. Usually, market exchange rates under value the purchasing power of currencies in developing countries, see Figure 3.4.

![Figure 3.4: Regional GDP per person expressed in MER and PPP on the basis of World Bank data aggregated to 17 global regions.](image)

Note: The left y-axis and columns compare absolute data, while the right y-axis and line graph compare the ratio between PPP and MER data. Source: van Vuuren and Alfsen (2006).

Clearly, derivation of PPP exchange rates requires analysis of a relatively large amount of data. 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) although the differences tend to be small.

On the question of whether PPP or MER should be employed in economic scenarios, the general recommendations are to use PPP where practical. This is certainly necessary when comparisons of income levels across regions are of concern. Models that analyse international trade and include trade as part of their economic projections, on the other hand, are better served by MER data given that trade takes place between countries in actual market prices. Thus, the choice of conversion factor depends on the type of analysis or comparison at being undertaken.

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3 See e.g. United Nations, (1993), (para 1.38): ‘When the objective is to compare the volumes of goods or services produced or consumed per head, data in national currencies must be converted into a common currency by means of purchasing power parities and not exchange rates. It is well known that, in general, neither market nor fixed exchange rates reflect the relative internal purchasing powers of different currencies. When exchange rates are used to convert GDP, or other statistics, into a common currency the prices at which goods and services in high-income countries are valued tend to be higher than in low-income countries, thus exaggerating the differences in real incomes between them. Exchange rate converted data must not, therefore, be interpreted as measures of the relative volumes of goods and services concerned.’
Nordhaus (2005) recommends, for principle and practical reasons, that economic growth scenarios should be constructed by using regional or national accounting figures (including growth rates) for each region, but using PPP exchange rates for aggregating regions and updating over time by use of a superlative price 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. Others (e.g. van Vuuren and Alfsen, 2006) also argue that the use of MER data in long-term modelling often is preferable given that model parameters usually are estimated on MER data and international trade within the models is based on MER. The real economic consequences of the choice of conversion rates will obviously depend on how the scenarios are constructed as well as on the type of model used for quantifying the scenarios. In some of the short-term scenarios (with a horizon to 2030) a bottom up approach is taken where assumptions about productivity growth and investment/saving decisions are the main drivers of growth in the models (e.g. McKibbin et al, 2004a,b). In long-term scenario models, a top down approach is more commonly used where the actual growth rates are more directly prescribed based on convergence or other assumptions about long-term growth potentials.

When it comes to emission projections, it is important to note that in a fully disaggregated (by country) multi-sector economic model of the global economy, aggregate index numbers play no role and the choice between PPP and MER conversion of income levels does not arise. However, in an aggregated model with consistent specifications, i.e., where model parameter estimation and model calibrations are all carried out based on consistent use of conversion factors, the effects of the choice of conversion measure on emissions should approximately cancel out. The reason can be illustrated by use of the Kaya identity (see Section 3.2.1), which decomposes the emissions as follows:

\[
GHG = \text{Population} \times \text{GDP per person} \times \text{Emissions per GDP}
\]

\[
GHG = POP \times \left( \frac{GDP}{POP} \right) \times \left( \frac{GHG}{GDP} \right)
\]

where GHG stands for emissions of greenhouse gases, GDP stands for economic output, and POP stands for population size.\(^4\)

Given this relationship, emission scenarios can be represented, explicitly based on estimates of population development, economic growth, and development of emission intensity.

Often, population is projected to grow along a pre-described (exogenous) path, while economic activity and emission intensities are projected based on differing assumptions from scenario to scenario. The economic growth path can be based on historical growth rates, convergence assumptions, or on fundamental growth factors like saving and investment behaviour, productivity changes, etc. Similarly, future emission intensities can be projected based on historical experiences, economic factors like labour productivity or other key factors determining structural changes in an economy, or technological development. The numerical expression of GDP clearly is dependent on conversion measures; thus GDP expressed in PPP will deviate from GDP expressed in MER, more so for developing countries. However, when it comes to calculating emissions (or other physical measures like energy), the Kaya identity shows that the choice between MER or PPP based representations of GDP will not matter, since emission intensity will change (in a compensating manner) when the GDP numbers change. While using PPP values necessitates using lower economic growth rates for developing countries under the convergence assumption, it is also necessary to adjust the relationship between income and demand for energy with lower economic

\(^4\) Other components could be introduced in the identity, like for instance energy use, without changing the argument.
growth leading to slower improvements in energy intensities. Thus, if a consistent set of metrics is employed, the choice of metric should not appreciably affect the final emission level.

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. Analysis of their work indicates that these results critically depend on, among other things, the combination of convergence assumptions and the mathematical approximation used between MER-GDP and PPP-GDP. In the Manne and Richels work for instance, autonomous efficiency improvements (AEI) is determined as a percentage of economic growth and estimated on the basis of MER data. In going from MER to PPP, the economic growth rate declines as expected, leading to a decline in the autonomous efficiency improvement. It is questionable however, whether it is realistic not to change the AEI rate when changing conversion measure. Holtmark and Alfsen (2004a,b), on the other hand, showed that in their simple model consistent replacement of the metric (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.

In summary, available evidence indicates that the differences between projected emissions using MER exchange rates and PPP exchange rates are small in comparison to the uncertainties represented by the range of scenarios and the likely impacts of other parameters and assumptions made in developing scenarios, e.g., technological change. The debate clearly shows, however, the need for modellers to be more transparent in explaining conversion factors as well as taking care in determining exogenous factors used for their economic and emission scenarios.

3.2.1.5 Energy use

Future evolution of energy systems is a fundamental determinant of GHG emissions. In most models, energy demand growth is a function of key driving forces such as demographic change and the level and nature of human activities such as mobility, information processing, and industry. In addition, the type of energy consumed is also important. While Chapters 4 through 11 report on medium term projections for different parts of the energy system, long-term energy projections are reported here. Figure 3.5 compares the range of the 153 SRES and pre-SRES scenarios with 133 new, post-SRES, long-term energy scenarios in the literature. The ranges are comparable, with small changes on the lower and upper bounds, and a shift downwards with respect of the median development. In general, the energy growth observed in the newer scenarios does not deviate significantly from the previous ranges as reported in the SRES report. However, most of the scenarios reported here have not adapted the lower population levels discussed in 3.2.1.1.

In general, the same situation exists for underlying trends as represented by changes in energy intensity, expressed as gigajoule (GJ)/GDP, and change in the carbon intensity of the energy system (CO$_2$/GJ) as shown in Figure 3.6. In all scenarios, energy intensity improves significantly across the century - with a mean annual intensity improvement of 1.0%. The 90% range of the annual average intensity improvement is between 0.5 and 1.9% (which is fairly consistent with historic variation in this factor). This range in fact implies a difference in total energy consumption in 2100 of more than 300% - indicating the importance of the uncertainty associated with this ratio. The carbon intensity is more constant in scenarios without climate policy. The mean annual long-term improvement rate over the course of the 21st century is 0.4%, while the uncertainty range is again relatively large (-0.2 to 1.5%). On the high end of this range scenarios are found that assume that energy technologies without CO$_2$ emissions become competitive without climate policy as a result of increasing fossil fuel prices and rapid technology progress for carbon free technologies. Scenarios with a low carbon intensity improvement coincide with scenarios with a large fossil fuel base, less resistance to coal
consumption or lower technology development rates for fossil free energy technologies. The long-term historical trend is one of declining carbon intensities. Since 2000 however carbon intensities are slightly increasing, which is primarily due to increasing use of coal. Just a few scenarios assume the continuation of the present trend of increasing carbon intensities. One of the reasons might be that just a few of the recent scenarios include the effect of high oil prices.

![Graph](image)

**Figure 3.5**: Comparison of 153 SRES and pre-SRES baseline energy scenarios in the literature compared with the 133 more recent, post-SRES scenarios. The ranges are comparable, with small changes on the lower and upper bounds.

*Note: Two vertical bars on the right extend from the minimum to maximum of the distribution of scenarios by 2100. The horizontal bars indicate the 5th, 25th, 50th, 75th and the 95th percentiles of the distributions.*

![Graph](image)

**Figure 3.6**: Development of carbon intensity of energy (left) and primary energy intensity of GDP (right). Historical development and projections from SRES and pre-SRES scenarios compared to post-SRES scenarios.

*Note: The blue colored range illustrates the range of 142 carbon intensity and 114 energy intensity - SRES and pre SRES non-intervention scenarios.*

*Source: After Nakićenović et al. 2006*
3.2.1.6 Land use change and land use management

Understanding land-use and land cover changes is crucial to understanding climate change. Even if land activities are not considered as subject to mitigation policy, the impact of land use change on emissions, sequestration, and albedo plays an important role in radiative forcing and the carbon cycle.

Over the past several centuries, human intervention has markedly changed land surface characteristics, in particular through large scale land conversion for cultivation (Vitousek et al., 1997). Land cover changes have an impact on 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 past millennium are thought to have had a global cooling effect (Brovkin et al., 1999). Biogeochemical effects result from 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 206 and 333 Pg CO$_2$ (McGuire et al., 2001), and as much as 572 Pg CO$_2$ for the entire industrial period 1850–2000, roughly a third of total anthropogenic carbon emissions over this period (Houghton, 2003). In addition, land management activities (e.g., cropland fertilization and water management, manure management and forest rotation lengths) also affect land based emissions of CO$_2$ and non-CO$_2$ GHGs, where agricultural land management activities are estimated to be responsible for the majority of global anthropogenic methane (CH$_4$) and nitrous oxide (N$_2$O) emissions. For example, USEPA (2006a) estimated that agricultural activities were responsible for approximately 52 and 84% of global anthropogenic CH$_4$ and N$_2$O emissions respectively in the year 2000, for a net contribution from non-CO$_2$ GHGs of 14% of all anthropogenic greenhouse gas emissions that year.

Projected changes in land use were not explicitly represented in carbon cycle studies until recently. Previous studies of the effects of future land use changes on the global carbon cycle employed trend extrapolations (Cramer et al., 2004), extreme assumptions about future land use changes (House et al., 2002), or derived trends of land use change from the SRES story lines (Levy et al., 2004). However, recent studies (e.g., Brovkin et al., 2006; Matthews et al., 2003; Gitz and Ciais, 2004) have shown that land use, as well as feedbacks in the society-biosphere-atmosphere system (e.g., Strengers et al., 2004), must be considered for realistic estimates of the future development of the carbon cycle; thereby providing further motivation for on-going development to explicitly model land and land use drivers in global integrated assessment and climate economic frameworks. For example, in a model comparison study of six climate models of intermediate complexity, Brovkin et al. (2006) concluded that land-use changes contributed to a decrease in global mean annual temperature in the range of 0.13 – 0.25 °C, mainly during the 19th century and the first half of the 20th century, which is in line with conclusions from other studies, like Matthews et al. (2003).

In general, land use 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). Non-market values — both use and non-use such as environmental services and species existence values respectively — will also shape land use outcomes.

Food demand is a dominant land use driver, and population and economic growth are the most significant food demand drivers through per person consumption. Total world food consumption is expected to increase by greater than 50% by 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 person...
meat consumption is expected to show a strong global increase, on the order of 25% by 2030, with faster growth in developing and transitional countries of more than 40 and 30%, respectively (Bruinsma, 2003; Cassman et al., 2003). The Millennium Ecosystem Assessment (MA) 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). Additional cropland is expected to be required to support these projected increases in demand. Beyond 2050, food demand is expected to level off with population.

Technological change is also a critical driver of land use, and a critical assumption in land use projections. For example, Sands and Leimbach (2003) suggest that globally 800 million hectares of cropland expansion could be avoided with a 1.0% annual growth in crop yields. Similarly, Kurosawa (2006) estimates decreased cropland requirements of 18% by 2050, relative to 2000, with 2% annual growth in global average crop yields. Alternatively, the MA scenarios implement a more complex representation of yield growth projections that, in addition to autonomous technological change, reflect the changes in production practices, investments, technology transfer, environmental degradation, and climate change. The net effect is positive but declining productivity growth over time for some commodities due in large part to diminishing marginal technical productivity gains and environmental degradation. In all these studies, increasing (decreasing) net productivity per hectare results in reduced (increased) cropland demand.

Also important to land use projections are potential changes in climate. For instance, rising temperatures and CO\textsubscript{2} fertilization may improve regional crop yields in the near term, thereby reducing pressure for additional cropland and resulting in increased afforestation. However, modelling the beneficial impacts of CO\textsubscript{2} fertilization is not as straightforward as once thought. Recent results suggest: lower crop productivity improvements in the field than shown previously with laboratory results (e.g., Ainsworth and Long, 2005); likely increases in tropospheric ozone and smog associated with higher temperatures that will depress plant growth and partially offset CO\textsubscript{2} fertilization; expected increases in the variability of annual yields; CO\textsubscript{2} effects favouring C3 plants (e.g., wheat, barley, potatoes, rice) over C4 plants (e.g., maize, sugar cane, sorghum, millet) while temperature increases favour C4 over C3 plants; potential decreased nutritional content in plants subjected to CO\textsubscript{2} fertilization and increased frequency of temperature extremes; and increases in forest disturbance frequency and intensity. See the WGII report, Chapter 5, for an overall discussion of these issues and this literature. Long term projections need to consider these issues as well as examine the potential limitations or saturation points of plant responses. However, to date, long term scenarios from integrated assessment models are only just beginning to represent climate feedbacks on terrestrial ecosystems, much less fully account for the many effects. Current integrated assessment representations only consider CO\textsubscript{2} fertilization and changes in yearly average temperature, if they consider climate change effects at all (e.g., USCCSP, 2006; van Vuuren et al., 2007).

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 (UNEP, 2002), the Millennium Ecosystem Assessment (2005), and some of the EMF-21 Study models (Kurosawa, 2006; van Vuuren et al., 2006-a; Rao and Riahi, 2006; Jakeman and Fisher, 2006; Riahi et al., 2006; van Vuuren et al., 2007). Recent sector specific economic studies have also contributed global land use projections for climate analysis, especially for forestry (Sand and Leimbach, 2003; Sohngen and Mendelsohn, 2003; Sohngen and Mendelsohn, 2007; Sathaye et al., 2006; Sohngen and Sedjo, 2006). In general, the post-SRES scenarios, though scarce in number for agricultural land use, have
projected increasing global cropland area, smaller forest land area, and mixed results for changes in global grassland (Figure 3.7). Unlike the SRES land use scenarios that span a broader range while representing diverse storylines, the post-SRES scenarios, for forestry in particular, illustrate greater convergence across models on projected land use change.

Figure 3.7: Global cropland (a), forest land (b) and grassland (c) projections (2010 = 1; shaded areas indicate SRES scenario ranges, post-SRES scenarios denoted with solid lines)

Notes: IMAGE-EMF21 = van Vuuren et al. (2006-a) scenario from EMF-21 Study; IMAGE-MA-xx = Millennium Ecosystem Assessment (2005) scenarios from the IMAGE model for four storylines (GO = Global Orchestration, OS = Order from Strength, AM = Adapting Mosaic, TG = TechnoGarden); AgLU-x.x% = Sands and Leimbach (2003) scenarios with x.x% annual growth in crop yield; GTM-2003 = Sohngen and Mendelsohn (2003) global forest scenario; GTM-EMF21 = Sohngen and Sedjo (2006) global forest scenario from EMF-21 Study; GCOMAP-EMF21 = Sathaye et al. (2006) global forest scenario from EMF-21 Study; GRAPE-EMF21 = Kurosawa (2006) scenario from EMF-21 Study
Most post-SRES global scenarios project significant changes in agricultural land caused primarily by regional changes in food demand and production technology. Scenarios with larger amounts of land used for agriculture 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 projected to lead to a sizeable expansion (up to 40%) of agricultural land between 1995 and 2100 (Figure 3.7). Conversely, lower population growth and food demand, and more rapid technological change, are projected to result in lower demand for agricultural land (as much as 20% less global agricultural acreage by the end of the century). In the near-term, almost all scenarios suggest an increase in cropland acreage and decline in forest land to meet projected increases in food, feed, and livestock grazing demands over the next few decades. Cropland changes range from -18 to +69% by 2050 relative to 2000 (-123 to +1158 million hectares) and forest land changes range from -18 to +3% (-680 to +94 million hectares) by 2050. The changes in global forest generally mirror the agricultural scenarios; thereby, illustrating both the positive and negative aspects of some existing global land modelling. Most of the long-term scenarios 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 agricultural and forest products and conservation demands.

Without incentives or technological innovation, biomass crops are currently not projected to assume a large share of global business as usual land cover - no more than about 4% by 2100. Until long-run energy price expectations rise (due to a carbon price, economic scarcity, or other force), biomass and other less economical energy supply technologies (some with higher greenhouse gas emissions characteristics than biomass), are not expected to assume more significant baseline roles.

### 3.2.2 Emissions

The span of CO\(_2\) emissions across baseline scenarios in the literature is still large, with emissions in 2100 ranging from 10 to around 250 GtCO\(_2\). The wide range of future emissions is a result of the uncertainties in the main driving forces, such as population growth, economic development, and energy production, conversion, and end use, as described in the previous section.

#### 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 cement production and sometimes feedstocks.\(^5\) Figure 3.8 compares the range of the pre-SRES and SRES baseline scenarios with the post-SRES baseline scenarios. The figure shows that the scenario range has remained almost the same since the SRES. There seems to have been an upwards shift on the high and low end, but careful consideration of the data shows that this is caused by only very few scenarios and the change is therefore not significant. The median of the recent scenario distribution has shifted downwards slightly from 75 GtCO\(_2\) by 2100 (pre-SRES and SRES) to about 60 GtCO\(_2\) (post SRES). The median of the recent literature corresponds thus roughly to emissions levels of the intermediate SRES-B2 scenarios. The majority of scenarios, both pre- and post-SRES indicate an increase of emissions across most of the century, resulting in a range of 2100 emissions of 17 to 135 GtCO\(_2\) emissions from energy and industry (90\(^{th}\) percentile of the full scenario distribution). Also the range of emissions depicted by the SRES scenarios is

\(^5\) 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 from land-use changes.
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, 2006).

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 fuel reserves reported in the literature. Some models may have decreased oil and gas use in this context, leading to higher coal use (and thus higher emissions).

Figure 3.8: Comparison of the SRES and pre-SRES energy-related and industrial CO\textsubscript{2} emissions scenarios in the literature with the post-SRES, scenarios.

Note: Two vertical bars on the right extend from the minimum to maximum of the distribution of scenarios and indicate the 5th, 25th, 50th, 75th and the 95th percentiles of the distributions by 2100

Source: After Nakicenovic et al. 2006

Analysis of scenario literature using the Kaya identity shows that pre- and post-SRES baseline scenarios indicate a continuous decline of the primary energy intensity (EJ/GDP), while the change in the carbon intensity (CO\textsubscript{2}/E) is much slower - or even stable (see Figure 3.8 and section 3.2.1.3) only in the post-SRES scenarios. In other words, in the absence of climate policy, structural change and energy efficiency improvement do contribute to lower emissions, but changes in the energy mix have a much smaller (or even zero) contribution. This conclusion is true for both the pre-SRES and SRES as well as the post-SRES scenario literature.

Baseline or reference emissions projections generally come from 3 types of studies: 1) studies meant to represent a ‘best-guess’ of what might happen if present-day trends and behaviour continues; 2) studies with multiple baseline scenarios under comprehensively different assumptions (storylines); and 3) studies based on a probabilistic approach. In literature since TAR, some discussion of the purpose of these approaches has occurred (see Schneider, 2001; Grübler et al., 2002 and Webster et
al., 2002). In Figure 3.9 (left panel) a comparison of the outcomes of some prominent examples of these approaches is made by comparing the outcome of baselines scenarios reported in the set of EMF-21, representing the ‘best-guess’ approach, to the outcomes of the SRES scenarios, representing the storyline approach. In the right panel the SRES range is compared to the probabilistic approach (see Webster et al., 2002; Richels et al., 2004 for the probability studies).

The figure shows that the range of different models participating in the EMF-21 study is somewhat smaller than those from SRES and the probabilistic approach. The range of EMF-21 scenarios arises from different modelling approaches and from modeller’s insights into ‘the mostly likely values’ for driving forces. The two probabilistic studies and SRES 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 probabilistic studies tends to be between these extremes. Overall, the three different approaches seem to lead to consistent results, confirming the range of emissions reported in Figure 3.9 and confirming the emission range of scenarios used for TAR.

**Figure 3.9:** Comparison of different long-term scenario studies for CO₂ emissions. Left panel: IPCC SRES, EMF-21 range (grey area) indicating the range of the lowest and highest reported values in the EMF-21 study (Weyant et al., 2006). Right panel: Webster et al. (2002) and Richels et al. (2004) indicating the mean (markers) and 95% intervals of the reported ranges of these studies (for the latter, the 95% interval of the combined range for optimistic and pessimistic technology is shown).

### 3.2.2.2 Anthropogenic land emissions and sequestration

Some of the first global integrated assessment scenario analyses to account for land use related emissions were the IS92 scenario set (Leggett et al., 1992) and the SRES scenarios (Nakicenovic et al., 2000). However, out of the six SRES models, only four dealt with land use specifically (MiniCAM, MARIA, IMAGE 2.1, AIM) of which MiniCAM and MARIA used more simplified land use modules. ASF and MESSAGE also simulated land use emissions, however ASF did not have a specific land use module and MESSAGE incorporated land use results from the AIM model (IPCC, 2000). Although SRES was a seminal contribution to scenario development, the treatment of land use emissions was not the focus of this assessment; and, therefore, neither was the modelling of land use drivers, land management alternatives, and the many emissions sources, sinks, and GHGs associated with land.

While some recent assessments, like the Third Global Environment Outlook of UNEP (UNEP, 2002) and the Millennium Ecosystem Assessment (Carpenter et al., 2005), have evaluated land
based environmental outcomes (global environment and ecosystem goods and services respectively), the Energy Modelling Forum’s 21st Study (EMF-21) was the first large scale exercise with a special focus on land as a climate issue. In EMF-21, the integrated assessment models incorporated non-CO₂ greenhouse gases, like those from agriculture, and carbon sequestration in managed terrestrial ecosystems (Kurosawa, 2006; van Vuuren et al., 2006-a; Rao and Riahi, 2006; Jakeman and Fisher, 2006). A few additional papers have subsequently improved upon their EMF-21 work (Riahi et al., 2006; van Vuuren et al., 2007). In general, the land use change carbon emissions scenarios since SRES project high global annual net releases of carbon in the near future that decline over time, leading to net sequestration by the end of the century in some scenarios (see Figure 3.10). The clustering of the non-harmonized post-SRES scenarios in Figure 3.10 suggests a degree of expert agreement that the decline in annual land use change carbon emissions over time will be less dramatic (slower) than suggested by many of the SRES scenarios. Many of the post-SRES scenarios project a decrease in net deforestation pressure over time as population growth slows and crop and livestock productivity increase; and, despite continued projected loss of forest area in some scenarios (Figure 3.6), carbon uptake from afforestation and reforestation result in net sequestration.

There also seems to be a consensus in recent non-CO₂ GHG emissions baseline scenarios that agricultural CH₄ and N₂O emissions will increase until the end of this century, potentially doubling in some baselines (see Table 3.1; Kurosawa, 2006; van Vuuren et al., 2006-a; Rao and Riahi, 2006; Jakeman and Fisher, 2006; Riahi et al., 2006; van Vuuren et al., 2007). The modelling of agricultural emission sources varies across scenarios, with livestock and rice paddy methane and crop soil nitrous oxide emissions consistently represented. However, the handling of emissions from biomass burning and fossil fuel combustion are inconsistent across models; and cropland soil carbon fluxes are generally not reported, likely due to the fact that soil carbon sequestration mitigation options are not currently represented in these models.

Figure 3.10: Baseline land-use change and forestry carbon net emissions
Notes: MESSAGE-EMF21 = Rao and Riahi (2006) scenario from EMF-21 Study; GTEM-EMF21 = Jakeman and Fisher (2006) scenario from EMF-21 Study; MESSAGE-A2r = Riahi et al. (2006) scenario with revised SRES-A2 baseline; IMAGE 2.3 = van Vuuren et al. (2007) scenario; see Figure 3.7 notes for additional scenario references. The IMAGE 2.3 LUCF baseline scenario also emits non-CO₂ emissions (CH₄ and N₂O) of 0.26, 0.30, 0.16 GtCO₂-eq in 2030, 2050, and 2100 respectively.
As noted in Section 3.2.1.4, climate change feedbacks could have a significant influence on long-term land use and, to date, are only partially represented in long-term modelling of land scenarios. Similarly, climate feedbacks can also affect land-based emissions. For instance, rising temperatures and CO\textsubscript{2} fertilization can influence the amount of carbon that can be sequestered by land and may also lead to increased afforestation due to higher crop yields. Climate feedbacks in the carbon cycle could be extremely important. For instance, Leemans et al. (2002) showed that CO\textsubscript{2} fertilization and soil respiration could be as important as the socio-economic drivers in determining the land use emissions range.

In addition, potentially important additional climate feedbacks in the carbon-climate system are currently not accounted for in integrated assessment scenarios. Specifically, new insights suggest that soil drying and forest dieback may naturally reduce terrestrial carbon sequestration (Cox et al., 2000). However, these studies, as well as studies that try to capture changes in climate due to land use change (Sitch et al., 2005) have thus far not been able to provide definitive guidance. A modelling system that fully couples land use change scenarios with a dynamic climate-carbon system is required in the future for such an assessment.

**Table 3.1:** Baseline global agricultural non-CO\textsubscript{2} greenhouse gas emissions from various long-term stabilization scenarios (GtCO\textsubscript{2eq})

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Non-CO\textsubscript{2} GHG agricultural emissions sources represented*</th>
<th>CH\textsubscript{4}</th>
<th>N\textsubscript{2}O</th>
<th>N\textsubscript{2}O</th>
<th>CO\textsubscript{2}</th>
<th>CO\textsubscript{2}</th>
<th>CO\textsubscript{2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>GTEM-EMF21</td>
<td>Enteric, manure, paddy rice, soil (N\textsubscript{2}O)</td>
<td>2.09 2.88 4.28 nm nm</td>
<td>1.95 2.60 3.64 nm nm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MESSAGE-EMF21</td>
<td>Enteric, manure, paddy rice, soil (N\textsubscript{2}O)</td>
<td>2.58 3.42 6.05 6.00 5.06</td>
<td>2.57 3.48 4.65 3.79 2.32</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IMAGE-EMF21</td>
<td>Enteric, manure, paddy rice, soil (N\textsubscript{2}O and CO\textsubscript{2}), biomass &amp; agricultural waste burning, land clearing</td>
<td>3.07 4.15 4.34 4.37 4.55</td>
<td>2.02 2.75 3.11 3.23 3.27</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRAPE-EMF21</td>
<td>Enteric, manure, paddy rice, soil (N\textsubscript{2}O), biomass &amp; agricultural waste burning</td>
<td>2.59 2.65 2.85 2.82 2.76</td>
<td>2.79 3.31 3.84 3.93 4.06</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MESSAGE-A2r</td>
<td>Enteric, manure, paddy rice, soil (N\textsubscript{2}O)</td>
<td>2.58 3.43 4.78 5.52 6.57</td>
<td>2.57 3.48 4.37 4.77 5.22</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IMAGE 2.3</td>
<td>Enteric, manure, paddy rice, soil (N\textsubscript{2}O and CO\textsubscript{2}), biomass &amp; agricultural waste burning, land clearing</td>
<td>3.36 3.95 4.41 4.52 4.46</td>
<td>2.05 2.48 2.93 3.07 3.06</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* CO\textsubscript{2} emissions from fossil fuel combustion are tracked as well, but frequently reported (and mitigated) under other sector headings (e.g., energy, transportation).

Notes: SAR GWPs used to compute carbon equivalent emissions. nm = not modelled. The GTEM-EMF21 scenario ran through 2050. See Figure 3.7 and 3.10 notes for the scenario references.

### 3.2.2.3 Non-CO\textsubscript{2} greenhouse gas emissions

The emissions scenario chapter in TAR (Morita et al., 2001) recommended that future research should include GHGs other than CO\textsubscript{2} in new scenarios work. The reason was that at that time, certainly regarding mitigation, most of the scenarios literature was still primarily focused on CO\textsubscript{2} emissions from energy. Nevertheless, some multigas scenario work existed, including the SRES baseline scenarios, but also some other modelling efforts (Manne and Richels 2001, Babiker et al. 2001, Tol 1999). The most important non-CO\textsubscript{2} gases include: methane (CH\textsubscript{4}), nitrous oxide (N\textsubscript{2}O), and a group of fluorinated compounds (F-gases, i.e., HFCs, PFCs, and SF\textsubscript{6}). Since the TAR, the number of modelling groups producing long-term emission scenario of non-CO\textsubscript{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 emissions related sectors are few, i.e., energy, industry, and land use, non-CO$_2$ emissions originate from a larger and more diverse set of economic sectors. Table 3.2 gives a list of major GHG emitting sectors and their corresponding emissions estimated for 2000. Note that there is significant uncertainty for emissions for some sources of the Non-CO$_2$ gases, and the table summarizes the central values from Weyant et al., 2006, which has been used in long-term multigas scenario studies of the EMF-21. 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).

The most important work on non-CO$_2$ GHG emissions scenarios has been done in the context of EMF-21 (de la Chesnaye and Weyant, 2006). The EMF-21 study updated the capability of long-term integrated assessment models for modelling non-CO$_2$ GHG emissions. The results of the study are illustrated in Figure 3.11.

Evaluating the long-term projections of anthropogenic methane emissions from the EMF-21 data show a significant range in the estimates but this range is consistent with that found in SRES. The methane emission differences in SRES are due to the different storylines. The differences in the EMF-21 reference cases are due 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 modelling groups employed various methods of representing methane emissions in their models and also made different assumptions about how specific methane emission factors for each economic sector change over time. Finally, the degree to which agricultural activities are represented in the models differs substantially. For example, some models represent all agricultural output as one large commodity, ‘agriculture,’ while others have considerable disaggregation. Interestingly, the latter group of models tend to find slower emissions growth rates (see van Vuuren et al., 2006-b).

The range of long-term projections of anthropogenic nitrous oxide emissions is wider than for methane in the EMF-21 data. Note that for N$_2$O, base year emissions of the different models differ substantially. Two factors may contribute to this. First, different definitions exist of what should be regarded as human-induced and natural emissions in the case of N$_2$O emissions from soils. Second, some models do not include all emission sources.

The last group of non-CO$_2$ gases are fluorinated compounds which including hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF$_6$). The global total emissions of these gases are almost 450 MtCO$_2$-eq or slightly over 1% of all GHG for 2000. While the emissions of some fluorinated compounds are projected to decrease, many are expected to grow substantially because of the 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. Total emissions of non-CO$_2$ GHG are projected to increase, but somewhat less rapidly than CO$_2$ emissions due to agricultural activities growing less than energy use.

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6 In the EMF-21 study, reference case scenarios were considered to be ‘modeller’s choice’ where harmonization of input parameters and exogenous assumptions was not sought.
Table 3.2: Global Anthropogenic GHG Emissions for 2000 at sector level as used in EMF-21 studies (MtCO$_2$-eq/yr)

<table>
<thead>
<tr>
<th>Sector sub-total &amp; Percent of Total</th>
<th>Sub-sectors</th>
<th>CO$_2$</th>
<th>CH$_4$</th>
<th>N$_2$O</th>
<th>F-gases</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENERGY</td>
<td>Coal</td>
<td>8,133</td>
<td>451</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nat Gas</td>
<td>4,800</td>
<td>895</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Petroleum Syst</td>
<td>10,476</td>
<td>62</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stationary/Mobile Sources</td>
<td>59</td>
<td></td>
<td>224</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>25,098</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>67%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LUCF 1 and AGRICULTURE</td>
<td>LUCF and Agriculture (net)</td>
<td>3,435</td>
<td>2,607</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Soils</td>
<td></td>
<td>491</td>
<td>187</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Biomass</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Enteric Fermentation</td>
<td>1,745</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Manure Management</td>
<td>224</td>
<td>205</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rice</td>
<td>649</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>9,543</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>25%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>INDUSTRY</td>
<td>Cement</td>
<td>829</td>
<td>158</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Adipic &amp; Nitric Acid Prd</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>HFC-23</td>
<td></td>
<td></td>
<td></td>
<td>95</td>
</tr>
<tr>
<td></td>
<td>1,434 PFCs</td>
<td></td>
<td></td>
<td></td>
<td>106</td>
</tr>
<tr>
<td></td>
<td>4% SF6</td>
<td></td>
<td></td>
<td></td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>Substitution of ODS 2</td>
<td></td>
<td></td>
<td></td>
<td>191</td>
</tr>
<tr>
<td>WASTE</td>
<td>Landfills</td>
<td>781</td>
<td>81</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wastewater</td>
<td>565</td>
<td>81</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>11</td>
<td>11</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>1,448</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total All GHG</td>
<td>37,524</td>
<td>27,671</td>
<td>5,933</td>
<td>3,472</td>
</tr>
<tr>
<td></td>
<td>Gas as percent of total</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>74%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>16%</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>9%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes: 1/ LUCF is Land-use change and forestry.
2/ HFCs are used as substitutes for ODSs in a range of applications

Figure 3.11: Development of baseline emission in the EMF-21 scenarios (left) and comparison between EMF21 and SRES scenarios (right).

Source: de la Chesnaye and weyant (2006); see also Van Vuuren et al., 2006-b

3.2.2.4 Scenarios for air pollutants and other radiative substances

3.2.2.4.1 Sulphur dioxide emissions scenarios

Sulphur emissions are relevant for climate change modelling as they contribute to the formation of aerosols, which affect precipitation patterns and, taken together, reduce radiative forcing. Sulphur
emissions also contribute to regional and local air pollution. Global sulphur dioxide emissions have grown 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 considerably (Grübler, 2002). Implementation of emissions controls, a shift to lower sulphur 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 sulphur emissions (Smith et al., 2001). Conversely, with accelerated economic development, the growth of sulphur emissions in many parts of Asia has been high in recent decades, although growth rates have moderated recently (Streets et al., 2000a; Stern 2005; Cofala et al. 2006; Smith et al., 2004). A review of the recent literature indicates that there is some uncertainty concerning present global anthropogenic sulphur emissions, with estimates for the year 2000 between 55.2 MtS (Stern, 2005), 57.5 MtS (Cofala et al. 2006) and 62 MtS (Smith et al., 2004).7

Many empirical studies have explored the relationship between sulphur emissions and related drivers, such as economic development (see for example, Smith et al., 2004). The main driving factors that have been identified 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 an inverted U-shaped pattern of SO2 emissions, where emissions increase during early stages of industrialization, peak and then fall at higher levels of income, following a Kuznets curve (World Bank, 1992). This general trend is also apparent in most of the recent emissions scenarios in the literature.

Over time, new scenarios have generally produced lower SO2 emissions projections. A comprehensive comparison of SRES and more recent sulphur emissions scenarios is given in Van Vuuren and O’Neill (2006). Figure 3.12 illustrates that the resulting spread of sulphur emissions over the medium term (up to the year 2050) is predominantly due to the varying assumptions about the timing of future emissions control, particularly in developing countries.8 Scenarios at the lower bound assume the rapid introduction of sulphur control technologies on a global scale, and hence, a reversal of historical trends and declining emissions in the initial years of the scenario. Conversely, the upper bound of emissions are characterized by a rapid increase over coming next decades, primarily driven by increasing use of coal and oil at relatively low levels of sulphur control (SRES A1 and A2).

The comparison shows that overall, the SRES scenarios are fairly consistent with recent projections concerning the long-term uncertainty range (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 sulphur inventories for the year 2000 have shifted downward. Second, and perhaps more importantly, new information on present and planned sulphur legislation in some developing countries, such as India (Carmichael et al., 2002) and China (Streets et al., 2001) has become available. Anticipating this change in legislation, recent scenarios project sulphur emissions to peak earlier and at lower levels compared to SRES. Also the lower bound projections of the recent literature have shifted downward slightly compared to SRES.

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7 Note that the Cofala et al. (2006) inventory does not include emissions from biomass burning, international shipping and aircraft. In order to enhance comparability between the inventories, emissions from these sources (6 MtS globally) have been added to the original Cofala et al. values.

8 The Amann (2002) projections were replaced by the recently updated IIASA-RAINS projection from Cofala et al. (2006).
3.2.2.4.2 NO\textsubscript{x} emissions scenarios

The most important sources of NO\textsubscript{x} emissions are fossil fuel combustion and industrial processes, which combined with other sources such as natural and anthropogenic soil release, biomass burning, lightning, and atmospheric processes, 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. (2006). Fossil fuel combustion in the electric power and transport sectors is the largest source of NO\textsubscript{x}, with emissions largely being related to the combustion practice. In recent years, emissions from fossil fuel use in North America and Europe are either constant or declining. In most parts of Asia and other developing parts of the world, emissions have been increasing, mainly due to the growing transport sector (Cofala et al. 2006, Smith, 2005; WBCSD, 2004). However in the longer term, most studies project that NO\textsubscript{x} emissions in developing countries will saturate and eventually decline following the trend in the developed world. The pace of this trend is however uncertain. Emissions are projected to peak in the developing world as early as 2015 (WBCSD, 2004 focusing on the transport sector) and in worst cases around the end of this century (see the high emissions projection of Smith, 2005).

There have been very few global scenarios for NO\textsubscript{x} emissions since the earlier IS92 scenarios and SRES. An important characteristic of these (baseline) scenarios is that they consider air pollution legislation (in the absence of any climate policy). Some scenarios, such as those by Bouwman and van Vuure (1999) and Collins et al. (1999) often use IS92a as a ‘loose’ baseline, with new abatement policies added. Many scenarios report rising NO\textsubscript{x} emissions up to the 2020s (Figure 3.13), with the lower bound given by the short-term Cofala et al. (2006) reference scenario, projecting emissions to stay at about present levels for the next two to three decades. In the most recent longer term scenarios (Smith, 2005), NO\textsubscript{x} emissions range between 32 and 47 MtN by 2020, which corresponds to an increase in emissions of about 6 to 50% compared to 2000. The long-term spread is considerably larger, ranging from 9 to 74 MtN by 2100 (see Figure 3.13). The majority of the SRES scenarios (70%) lie within the range of the new Smith (2005) scenarios. However, the upper and lower bounds of the range of the recent projections have shifted downward compared to SRES.
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 as well as from gaseous precursors (Penner et al., 1993; Gray & Cass 1998). The main 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. Natural sources such as forest fires and savannah burning are other major contributors. There has recently been some research suggesting that carbonaceous aerosols may contribute to global warming (Hansen et al. 2000; Andrae 2001; Jacobson 2001, Ramaswamy et al., 2001). However, the uncertainty concerning the effects of BC and OC on the change in radiative forcing and hence global warming is still high (see Jacobson, 2001 and Penner et al., 2004).

In the past, BC and OC emissions have been poorly represented in economic and systems engineering models due to unavailability of data. For example, in IPCC’s Third Assessment Report, BC and OC estimates were developed by using CO emissions (IPCC, 2001e). One of the main reasons for this has been the lack of adequate global inventories for different emission sources. However, some detailed global and regional emission inventories of BC and OC have recently become available (Table 3.3). In addition, some detailed regional inventories are also available including Streets et al., 2000b and Kupiainen and Klimont, 2004. While many of these are comprehensive with regard to detail, considerable uncertainty still exists in the inventories, mainly due to the variety in combustion techniques for different fuels as well as measurement techniques. In order to represent these uncertainties, some studies, e.g., Bond et al. (2004), provide high, low and ‘best-guess’ values.
Table 3.3: Emission Inventories for Black and Organic Carbon (Tg/yr)

<table>
<thead>
<tr>
<th>Source</th>
<th>Estimate Year</th>
<th>Black carbon</th>
<th>Organic carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penner et al., 1993</td>
<td>1980</td>
<td>13</td>
<td>-</td>
</tr>
<tr>
<td>Cooke and Wilson, 1996</td>
<td>1984</td>
<td>14(^{1})</td>
<td>-</td>
</tr>
<tr>
<td>Cooke et al., 1999</td>
<td>1984</td>
<td>5.6-6.6(^{1})</td>
<td>7-10(^{1})</td>
</tr>
<tr>
<td>Bond et al., 2004</td>
<td>1996</td>
<td>4.7 (3-10)</td>
<td>8.9 (5-17)</td>
</tr>
<tr>
<td>Liousse et al., 1996</td>
<td>1997</td>
<td>12.3</td>
<td>81</td>
</tr>
<tr>
<td>Junker and Liousse, 2006</td>
<td>1997</td>
<td>5.7</td>
<td>9.5</td>
</tr>
</tbody>
</table>

\(^{1}\) Emissions from fossil-fuel use

The development in the inventories has resulted in the possibility of estimating future BC and OC emissions. Streets et al. (2004) use the fuel use information and technological change in the SRES scenarios to develop estimates of BC and OC emissions from both contained combustion as well as natural sources for all the SRES scenarios until 2050. Rao et al. (2005) and Smith and Wigley (2006) estimate BC and OC emissions until 2100 for two IPCC SRES scenarios, with an assumption of increasing affluence leading to an additional premium on local air quality. Liousse et al. (2005) use the fuel-mix and other detail in various energy scenarios and obtain corresponding BC and OC emissions.

The inclusion of technological development is an important factor in estimating future BC and OC emissions as even though absolute fossil fuel use may increase, a combination of economic growth, increased environmental consciousness, technology development and legislation could imply decreased pollutant emissions (Figure 3.14). Liousse et al. (2005) neglect the effects of technological change leading to much higher emission estimates for BC emissions in the long-term in some cases as compared to other studies like Streets et al. (2004), Rao et al. (2005) and Smith and Wigley (2006), all of which show declining emissions in the long-term. Another important factor that Rao et al. (2005) also account for is current and proposed environmental legislation. This suggests the necessity for technology rich frameworks that capture structural and technological change as well as policy dynamics in the energy system in order to estimate future BC and OC emissions.

Figure 3.14: Total BC (Left Panel) and OC (Right Panel) Emission Estimates in Scenarios from Different Studies.

Notes: Rao et al., (2005) include emissions from contained combustion only. Liousse et al. (2005), A2 not included as 2100 value of 100 Tg lies way above range.

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 such as East Asia (including China). In other developing
regions such as Africa and South Asia, slower technology penetration rates lead to much lower emission reductions. There is a large decline in emissions from the residential sector in the developing countries, due to the gradual replacement of traditional fuels and technologies with more efficient ones. Transport related emissions in both industrialized and developing countries decline in the long-term due to stringent regulations, technology improvements and fuel switching.

To summarize, an important feature of the recent scenario literature is the long-term decline in BC/OC emissions intensities per unit of energy use (or economic activity). The majority of the above studies thus indicate that the long-term BC and OC emissions might be decoupled from the trajectory of CO\textsubscript{2} emissions.

### 3.3 Mitigation scenarios

#### 3.3.1 Introduction

This section contains a discussion of methodological issues (3.3.2-3.3.4), followed by a focus on the main characteristics of different groups of mitigation scenarios with specific attention paid to new literature on non-CO\textsubscript{2} gasses and land use (3.3.5.5 and 3.3.5.6). Finally, short-term scenarios with a regional or national focus are discussed in Section 3.3.6.

#### 3.3.2 Definition of a stabilization target

Mitigation scenarios explore the feasibility and costs of achieving specified climate change or emissions targets often in comparison to a corresponding baseline scenario. The specified target itself is an important modeling and policy issue. Because Article 2 of United Nations Framework Convention on Climate Change (UNFCCC) states as its objective the ‘stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system’, most long-term mitigation studies have focused their efforts on GHG concentration stabilization scenarios. However, several other climate change targets may be chosen, e.g., rate of temperature change, radiative forcing, or climate change impacts (see e.g. Richels et al., 2004; Van Vuuren et al., 2006-b; Corfee-Morlot et al., 2005). In general, selecting a climate policy 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 Table 3.4). Selecting a climate target further down the cause-effect chain (e.g. temperature change, or even avoided climate impacts) provides for greater specification of a desired climate target, but decreases certainty on the required emission reductions to reach that target.

A commonly used target has been the stabilization of the atmospheric CO\textsubscript{2} concentration. If more than one GHG is included, most studies use the corresponding target of stabilizing 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 consequences for emission trajectories do not depend on climate sensitivity which adds an important uncertainty. The disadvantage is that a wide range of temperature impacts are possible for each radiative forcing level. Temperature targets, by contrast, provide a more direct first-order indicator of potential climate change impacts, but are less practical to implement in the real world, because of the uncertainty about the required emissions reductions.

Another approach is to calculate risks or probability of exceeding particular values of global annual mean temperature rise (see also Table 3.9). For example, den Elzen and Meinschhausen (2006) and
Hare and Meinshausen (2006) used different probability density functions of climate sensitivity in the MAGICC simple climate model to estimate relationships between the probability of achieving climate targets and required emission reductions. Studies by Richels et al. (2004), Yohe et al. (2004), den Elzen et al. (2006), Keppo et al. (2006), Kypreos (2006) have used a similar probabilistic concept in an economic context. The studies analyse the relationship between potential mitigation costs and the increase in probability of meeting specific temperature targets.

Table 3.4: Advantages and disadvantages of using different stabilisation targets

<table>
<thead>
<tr>
<th>Target</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mitigation Costs</td>
<td>Lowest uncertainty on costs</td>
<td>Very large uncertainty on global mean temperature increase and impacts.</td>
</tr>
<tr>
<td>Emissions Mitigation</td>
<td>Lower uncertainty on costs</td>
<td>Very large uncertainty on global mean temperature increase and impacts. Either needs a different metric to allow for aggregating different gasses (e.g. GWP) or forfeits opportunity of substitution.</td>
</tr>
<tr>
<td>Concentrations of different greenhouse gasses</td>
<td>Can be translated relatively easily into emission profiles (reducing uncertainty on costs).</td>
<td>Does not allow for substitution among gasses, thus loosing the opportunity for multigas cost reductions. Indirect link to the objective of climate policy (e.g., impacts).</td>
</tr>
<tr>
<td>Radiative forcing</td>
<td>Easy translation to emission targets, thus not including climate sensitivity in costs calculations. Does allow for full flexibility in substitution among gasses. Connects well to earlier work on CO₂ stabilisation. Can be expressed in terms of CO₂-equivalent concentration target, if preferred for communication with policy-makers.</td>
<td>Allows a wide range of CO₂-only stabilization targets due to substitutability between CO₂ and non-CO₂ emissions. Indirect link to the objective of climate policy (e.g., impacts).</td>
</tr>
<tr>
<td>Global mean temperature</td>
<td>Metric is also used to organize impact literature; and as has shown to be a reasonably proxy for impacts.</td>
<td>Large uncertainty on required emissions reduction as result of the uncertainty in climate sensitivity and thus costs.</td>
</tr>
<tr>
<td>Impacts</td>
<td>Direct link to objective of climate policies</td>
<td>Very large uncertainties in required emission reductions and costs.</td>
</tr>
</tbody>
</table>

Based on: Van Vuuren et al., 2006-b

The choice of different targets is not only relevant because it leads to different uncertainty ranges, but also because it leads to different strategies. Stabilization of one type of target, such as temperature, does not imply stabilization of other possible targets, such as sea level rise, radiative forcing, concentrations or emissions. For instance, a cost-effective way to stabilize temperature is not radiative forcing stabilization, but rather to allow radiative forcing to peak at a certain concentration, and then decrease with additional emissions reductions so as to avoid (delayed) further warming and stabilize global mean temperature (see Meinshausen, 2006; Khesqi et al., 2005; den Elzen et al., 2006). Finally, targets also can be defined to limit a rate of change, such as the rate of temperature change. While such targets have the advantage of providing a link to impacts related to the rate of climate change, strategies to achieve them may be more sensitive to uncertainties and thus, require careful planning. Rate of temperature change targets, for instance, may be difficult to achieve in the short-term even using multi-gas approaches (Manne and Richels, 2006; van Vuuren et al., 2006-a).
3.3.3 How to define substitution among gases

In multi-gas studies, a method is needed to compare different greenhouse gases with different atmospheric lifetimes and radiative properties. Ideally, the method would allow for substitution between gases in order to achieve mitigation cost reductions although it may not be suitable to ensure equivalence in measuring climate impact. Fuglestvedt et al. (2003) provide a comprehensive overview of the different methods that have been proposed along with their advantages and disadvantages. One of these methods, CO$_2$-equivalent emissions based on Global Warming Potentials (GWP), 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 and economic debate on the use of GWPs (that is, they are not based on economic considerations and use an arbitrary time horizon) the concept is in use under the UNFCCC, the Kyoto Protocol, and the United States climate policy. In addition, no alternative measure has attained comparable status to date.

Useful overviews of the mitigation and economic implication of substitution metrics are provided by Bradford (2001) and Godal (2003). Models that use intertemporal optimization can avoid the use of substitution metrics (such as GWPs) by optimizing the reductions of all gases simultaneously under a chosen climate target. Intertemporal optimization or perfect foresight models assume that economic agents know future prices and make decisions to minimize costs. Manne and Richels (2001) show using their model that using GWPs as the basis of substitution did not lead to the cost-optimal path (minimizing welfare losses) for the long-term targets analyzed. In particular, reducing methane early had no benefit for reaching the long-term target given its short life time in the atmosphere. Some models in the recent EMF-21 study validated this result (see de la Chesnaye and Weyant, 2006). Figure 3.15 shows the projected EMF-21 CO$_2$, CH$_4$, N$_2$O, 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 gases on the basis of intertemporal optimization. While for most of the gasses, there are no systematic differences between the results from the two groups, for methane and some F-gasses (not shown), there are clear differences related to the very different lifetimes of these gases. The models that do not use GWPs, do not substantially reduce CH$_4$ until the end of the time horizon. For models using GWPs, however, the reduction of CH$_4$ emissions in the first three decades is substantial: here, CH$_4$ reductions become a cost-effective near term abatement strategy despite the short-life time (Van Vuuren et al., 2006-b). It should be noted that if a short-term climate target is selected (e.g. rate of temperature change) then intertemporal optimization models would also favour early methane reductions.

While GWPs do not necessarily lead to the most cost-effective stabilization solution given a long-term target, they can be a practical choice nevertheless: in real-life policies an exchange metric is needed to facilitate emissions trading between gasses within a specified time period. Allowing such exchanges creates the opportunity for cost savings through ‘what and where flexibility’. It is appropriate to ask what are the costs of using GWPs versus not using them and whether other ‘real world’ metrics exist that could perform better. O’Neill (2003) and Johansson et al. (2005) have argued that the disadvantages of GWPs are likely to be outweighed by the advantages 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 GWP-based multi-gas strategy and a cost-optimal strategy. Aaheim et al. (2006) found that the cost of using GWPs compared with optimal weights depends on the ambition of climate policies. Postponing the early CH$_4$ reductions of the GWP-based strategy, as is suggested by intertemporal optimization, generally leads to larger increases of temperature in the 2000-2020 period. This is because the increased reduction of CO$_2$ from the energy sector also leads to reduction...
of sulphur emissions (hence the cooling associated with sulphur based aerosols) but allows the potential to be used later in the century.

![Figure 3.15](image)

**Figure 3.15:** Reduction of emissions in the stabilization strategies aiming for stabilization at 4.5 W/m² (multigas strategies) in EMF-21.

Notes: Range for models using GWPs (blue; standard deviation) versus those not using them (purple; full range). For the first group, all 9 reporting long-term models were used. For the second category, results of 2 of the 3 reporting models were used (the other model shows the same pattern with respect to the distribution among gasses but has a far higher overall reduction rate and as such an outlier).

Data source: de la Chesnaye and Weyant, 2006.

### 3.3.4 Emission pathways

Emission pathway studies often focus on specific questions with respect to the consequences of timing (in terms of environmental impacts) or overall reduction rates needed for specific long-term targets. (e.g. the emission pathways developed by Wigley *et al.*, 1996). A specific issue raised in the literature on emission pathways since TAR has been the issue of a temporary overshoot of the target (concentration, forcing, or temperature). Meinshausen (2006) use a simple carbon-cycle model to illustrate that for low concentration targets (i.e. below 3 W/m²/450 ppm CO₂-eq) overshoot is inevitable given the feasible maximum rate of reduction. Wigley (2003) argued that overshoot profiles may give important economic benefits. In response, O’Neill and Openheimer (2004) showed that the associated incremental warming of large overshoots may significantly increase the risks of exceeding critical climate thresholds to which ecosystems are known to be able to adapt.

Other emission pathways that lead to less extreme concentration overshoots may provide a sensible compromise between these two results. For instance, the ‘peaking strategies’ chosen by Den Elzen *et al.* (2006) show that it is possible to increase the likelihood of meeting the long-term temperature target or to reach targets with a similar likelihood at lower costs. Similar arguments for analysis of overshoot strategies are made by Harvey (2004), Kheshqi *et al.* (2005).

### 3.3.5 Long-term stabilization scenarios

A large number of studies focusing on climate stabilization have been published since TAR. Several model comparison projects contributed to the new literature, including the Energy Modeling Forum’s EMF-19 (Weyant, 2004) and EMF-21 studies (de la Chesnaye and Weyant, 2006) that focused on technology change and multigas studies, respectively, the IMCP (International Model Comparison Project) that focused on technological change (Ederhofer *et al.*, 2006), and the U.S. Climate Change Science Program (USCCSP, 2006). The updated emission scenario database (Hanaoka *et al.*, 2006; Nakicenovic *et al.*, 2006) includes a total of 151 new mitigation scenarios published since SRES.
Comparison of mitigation scenarios is more complicated now than at the time of the TAR because:

- Part of the modelling community has expanded their analysis to include non-CO$_2$ gases, while others have continued to focus solely on CO$_2$. As discussed in the previous section, multigas mitigation scenarios use different targets making comparison more complicated.
- Some recent studies developed scenarios that do not stabilize radiative forcing (or temperature) - but show a peak before the end of the modelling time horizon (in most cases 2100).
- At the time of TAR, many studies used the SRES scenarios as baselines for their mitigation analyses providing a comparable set of assumptions. Now, there is a broader range of underlying assumptions.

In this section, some metrics are introduced to group the CO$_2$-only and multigas scenarios so that they are reasonably comparable. In Figure 3.16 the reported CO$_2$ concentrations in 2100 are plotted against the 2100 total radiative forcing (relative to pre-industrial times). Figure 3.16 shows that a relationship exists between the two indicators. This can be explained by the fact that CO$_2$ forms by far the most important contributor to radiative forcing - and subsequently, a reduction in radiative forcing needs to coincide with a reduction in CO$_2$ concentration. The existing spread across the studies is caused by several factors, including differences in the rate of abatement among alternative gases, differences in specific forcing values for GHGs and other radiative gases (in particular aerosols), and differences in the atmospheric chemistry and carbon cycle models that are used. Here, the relationship is used to classify the available mitigation literature into six different classes that vary in the stringency of the climate targets. The most stringent group includes those scenarios that aim to stabilize radiative forcing below 3 W/m$^2$. This group also includes all CO$_2$-only scenarios that stabilise CO$_2$ concentrations below 400 ppm. The least stringent group of mitigation scenarios, in contrast, have a radiative forcing in 2100 above 6 W/m$^2$ - associated with CO$_2$ concentrations above 660 ppm. By far the most studied group of scenarios are those that aim to stabilize radiative forcing at 4 to 5 W/m$^2$ or 490 to 570 ppm CO$_2$ (see Table 3.5 below).

![Figure 3.16: Relationship of total radiative forcing vis-à-vis CO$_2$ concentration for the year 2100 (25 multigas stabilization scenarios for alternative stabilisation targets)](image-url)
Table 3.5: Classification of recent (Post-TAR) stabilization scenarios according to different stabilization targets and alternative stabilization metrics. Groups of stabilization targets were defined using the relationship in Figure 3.16

<table>
<thead>
<tr>
<th>Category</th>
<th>Additional Radiative forcing</th>
<th>CO₂ concentration</th>
<th>CO₂-eq. Concentration</th>
<th>Peaking year for CO₂ emissions</th>
<th>Change in global emissions in 2050 (% of 2000 emissions)</th>
<th>No. of scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2</td>
<td>3.0 – 3.5</td>
<td>400 – 440</td>
<td>490 – 535</td>
<td>2000 - 2020</td>
<td>-60 to -30</td>
<td>18</td>
</tr>
<tr>
<td>B</td>
<td>3.5 – 4.0</td>
<td>440 – 480</td>
<td>535 – 590</td>
<td>2010 - 2030</td>
<td>-30 to +5</td>
<td>21</td>
</tr>
<tr>
<td>C</td>
<td>4.0 – 5.0</td>
<td>480 – 570</td>
<td>590 – 710</td>
<td>2020 - 2060</td>
<td>+10 to +60</td>
<td>118</td>
</tr>
<tr>
<td>D</td>
<td>5.0 – 6.0</td>
<td>570 – 660</td>
<td>710 – 855</td>
<td>2050 - 2080</td>
<td>+25 to +85</td>
<td>9</td>
</tr>
<tr>
<td>E</td>
<td>6.0 – 7.5</td>
<td>660 – 790</td>
<td>855 – 1130</td>
<td>2060 - 2090</td>
<td>+90 to +140</td>
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<td></td>
<td></td>
<td></td>
<td>Total</td>
<td>177</td>
</tr>
</tbody>
</table>

Ranges correspond to the 15th to 85th percentile of the Post-TAR scenario distribution.

Note that the classification needs to be used with care. Each category includes a range of studies going from the upper to the lower boundary. The classification of studies was done on the basis of the reported targets (thus including modeling uncertainties). In addition, also the relationship, which was used to relate different stabilization metrics, is subject to uncertainty (see Figure 3.16).

The classification of scenarios, as given in Table 3.5, permits the comparison of multigas and CO₂-only stabilization scenarios according to groups of scenarios with comparable level of mitigation stringency. The studies have been classified on the basis of the reported targets, using the relationship from Figure 3.16 to permit comparability of studies using different stabilization metrics. The following section uses these categories (A1 to E) for analyzing the underlying dynamics of stabilization scenarios as a function of the stabilization target. It should be noted, however, that the classification is subject to uncertainty and needs thus to be used with care.

3.3.5.1 Emission reductions and timing

Figure 3.17 shows the projected CO₂ emissions associated with the new mitigation scenarios. In addition, the figure depicts the range of the TAR stabilization scenarios (more than 80 scenarios) (Morita et al., 2001). Independent of the stabilization level, scenarios show that the scale of the emissions reductions relative to the reference scenario increases over time. Higher stabilization targets do push back the timing of most reductions, even beyond 2100.

An increasing body of literature is assessing the attainability of very low targets of below 450 ppm CO₂ (e.g., van Vuuren et al., 2007, Riahi et al., 2006). These scenarios from class A1 and A2 extend the lower boundary beyond the range of TAR stabilization scenarios of 450 ppm CO₂ (see upper panels of Figure 3.17). The attainability of such low targets is shown to depend on: 1) using a wide range of different reduction options; and 2) the technology ‘readiness’ of advanced technologies, in particular the combination of bio-energy and carbon capture and geologic storage (BECCS). If biomass is grown sustainably, this combination may lead to negative emissions (Williams 1998, IPCC 2005). Rao and Riahi (2006), Azar et al. (2006) and Van Vuuren et al. (2007) all find that such negative emissions technologies might be essential for achieving very stringent targets.

The emission range for the scenarios with low and intermediate targets between 3.5 to 5 W/m² (scenarios in categories B and C) are consistent with the range of the 450 and 550 ppm CO₂ scenarios in TAR. Emissions in this category tend to show peak emissions around 2040 - with emissions in 2100 similar or slightly below emissions today. Although less rapid and forceful reductions are required than in the case of more stringent targets, studies focussing on this
stabilization category find that a wide portfolio of reduction measures would be needed to achieve such emission pathways in a cost effective way.

The two highest categories of stabilization scenarios (D and E) overlap with low-medium category baseline scenarios (see Section 3.2). This partly explains the relatively small number of new studies for these categories. The emission profiles of these scenarios are found to be consistent with the emissions ranges as published in the TAR.

Figure 3.17: Emissions pathways of mitigation scenarios for alternative groups of stabilization targets (Category A1 to E, see Table 3.5). The pink area gives the projected CO$_2$ emissions for the recent mitigation scenarios developed post TAR. Green shaded areas depict the range of more than 80 TAR stabilization scenarios (Morita et al., 2001). Category A1 and A2 scenarios explore stabilization targets below the lowest target of TAR.

Source: After Nakicenovic et al., 2006, and Hanaoka et al., 2006

There is a relatively strong relationship between the cumulative CO$_2$ emissions in the 2000-2100 period and the stringency of climate targets (see Figure 3.18). The uncertainties associated with
individual stabilization levels (shown by the different percentiles) are primarily due to the ranges associated with individual stabilization categories, substitutability of CO₂ and non-CO₂ emissions, different model parameterizations of the carbon cycle and partly also due to differences in emissions pathways (delayed reduction pathways can allow for somewhat higher cumulative emissions). In general, scenarios aiming for targets below 3 W/m² require cumulative CO₂ emissions around 1100 GtCO₂ (range of 800-1500 GtCO₂). The cumulative emissions increase for subsequently less stringent targets. The middle category (4-5 W/m²) requires emissions to be in the order of 3000 GtCO₂ (range of 2270-3920 GtCO₂). The highest category (>6W/m²) exhibit emissions on average around 5020 GtCO₂ (range of 4400 - 6600 GtCO₂).

![Figure 3.18: Relationship between the scenario's cumulative carbon dioxide emissions (2000-2100) and the stabilization target (stabilization categories A1 to E of Table 3.5). Data source: After Nakicenovic et al., 2006, and Hanaoka et al., 2006](image)

Also the timing of emission reductions depends on the stringency of the stabilization target. Timing of climate policy has been an important topic in the scenario literature. While some studies argue for early action for smooth transitions and stimulating technology development (e.g. Azar and Dowlatibadi, 1999; Van Vuuren and de Vries, 2001), others emphasize delayed response to benefit from better technology and higher CO₂ fertilization rates from natural systems at later points in time (e.g. Wigley et al., 1996; Tol, 2000; for a more elaborate discussion on timing see also Section 3.6). This implies that a given stabilization target can be consistent with a range of interim targets. Nevertheless, stringent targets require an earlier peak of CO₂ emissions (see Figure 3.19 and Table 3.5). In the majority of the scenarios of the most stringent groups (< 3 W/m²), emissions start to decline already before 2015 and are further reduced to less than 50% of today’s emissions by 2050 (Table 3.5). The emissions profiles of these scenarios indicate the need of near term infrastructure investments for a comparatively early decarbonization of the energy system. Achieving these low emissions trajectories require a comprehensive global mitigation effort including a further tightening of existing climate policies in Annex I countries, and simultaneous emission mitigation in developing countries, where most of the increase in emissions is expected in the coming decades.

For the medium group (4-5 W/m²) the peak of global emissions generally occurs around 2010 to 2030; followed by a return to 2000 levels on average around 2040 (with the majority of these scenarios returning to 2000 emissions levels between 2020 and 2060). For targets between 5-6

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9 Note that the percentiles are used for the illustration of the statistical properties of the scenario distributions, and should not be interpreted as likelihoods in any probabilistic context.
W/m², the median emissions peak around 2070. The figure also indicates that the uncertainty range is relatively small for the more stringent targets, illustrating the reduced flexibility of the emissions path and the requirement for early mitigation. For less stringent categories more flexibility in timing exists. Most of the stringent stabilization scenarios of category A1 (and some A2 scenarios) assume a temporal overshoot of the stabilization target (GHG concentration, radiative forcing, or temperature change) before the eventual date of stabilization between 2100 and 2150. Recent studies indicate that while such “overshoot” strategies might be inevitable for very low targets (given the climate system and socio-economic inertia), they might also provide important economic benefits. At the same time, however, studies note that the associated rate of warming from large overshoots might significantly increase the risk of exceeding critical climate thresholds. (for a discussion see Section 3.3.4).

The right-hand panel of Figure 3.19 illustrates the time at which CO₂ emissions will have to return to present levels. For stringent stabilization targets (below 4 W/m²; category A1, A2 and B) emissions return to present levels on average before the middle of this century, i.e., about one to two decades after the year that emissions peak. In most of the scenarios of the highest stabilization category (above 6 W/m²; category E) emissions could stay above present levels throughout the century.

**Figure 3.19:** Relationship between the stringency of the stabilization target (category A1 to E) and 1) the time at which CO₂ emissions have to peak (left-hand panel), and 2) the year at which emissions return to present (2000) levels.

Data source: After Nakicenovic et al., 2006, and Hanaoka et al., 2006.

The absolute level of the required emissions reduction does not only depend on the stabilization target, but also on the baseline emissions (see Hourcade et al., 2001). This is clearly shown in the right-hand panel of Figure 3.20, which illustrates the relationship between the cumulative baseline emissions and the cumulative emissions reductions for the stabilization scenarios (by 2100). In general, scenarios with high baseline emissions require a higher reduction rate to reach the same reduction target: this implies that the different reduction categories need to show up as diagonals in Figure 3.20. This is indeed the case for the range of studies and the ‘category averages’ (large triangles). As indicated in the figure, a scenario with high baseline emissions requires much deeper emission reduction to reach a medium stabilization target (sometimes more than 3600 GtCO₂) than a scenario with low baseline emissions to reach the most stringent targets (in some cases less than 1800 GtCO₂). For the same target (e.g. category C) reduction may differ from 370 to 5500 GtCO₂. This comes from the large spread of emissions in the baseline scenarios. While scenarios for both stringent and less stringent targets have been developed from low and high baseline scenarios, the
data suggest that, on average, mitigation scenarios aimed for the most stringent targets start from the lowest baseline scenarios.

![Graph showing cumulative emission reductions](image)

**Figure 3.20**: Relationship between required cumulative emissions reduction and carbon emissions in the baseline by 2030 (left-hand panel) and 2100 (right-hand panel).

Notes: Coloured rectangles denote individual scenarios for alternative stabilization targets (categories A1 to E). The large triangles indicate the averages for each category.

Data source: After Nakicenovic et al., 2006, and Hanaoka et al., 2006).

In the short-term (2030), the relationship between emission reduction and baseline is less clear given the flexibility in timing of emission reductions (left-hand panel in Figure 3.20). While the averages of the different stabilization categories are aligned in a similar way as discussed for 2100 (with exception of the A1 category for which the scenario sample is smaller than for the other categories); the uncertainty ranges here are very large.

### 3.3.5.2 GHG abatement measures

The abatement of GHG emissions can be achieved through a wide portfolio of measures in the energy, industry, agricultural and forest sectors (see also Edmonds *et al.*, 2004b; Pacala and Socolow, 2004; Metz and van Vuuren, 2006). Measures for reducing CO$_2$ emissions range from structural changes in the energy system and replacement of carbon-intensive fossil fuels by cleaner alternatives (such as a switch from coal to natural gas, or the enhanced use of nuclear and renewable energy) to demand-side measures geared toward energy conservation and efficiency improvements. In addition, the capturing of carbon during energy conversion processes with subsequent storage in geological formations (CCS) provide an approach for reducing emissions. Another important option for CO$_2$ emission reduction encompasses the enhancement of forest sinks through afforestation, reforestation activities and avoided deforestation.

In the energy sector the above mentioned options can be grouped into two principal measures for achieving CO$_2$ reductions: 1) improving the efficiency of energy use (or measures geared toward energy conservation); and 2) reducing the emissions per unit of energy consumption. The latter comprises the aggregated effect of structural changes in the energy systems and the application of CCS. To explore the importance of these two strategies, a response index has been calculated (based on the full set of stabilization scenarios from the database). This index is equal to the ratio of the reductions achieved by energy efficiency over those achieved by carbon intensity improvements (Figure 3.21). Similar to Morita and Robinson (2001) it is found that the mitigation response to reduce CO$_2$ emissions would shift over time from initially focusing on energy efficiency reductions in the beginning of the 21$^{st}$ century to more carbon intensity reduction in the latter half of the
century (Figure 3.21). The amount of reductions coming from carbon intensity improvement is more important for the most stringent scenarios. The main reason is that in the second half of the century increasing costs of further energy efficiency improvements and decreasing costs of low-carbon or carbon-free energy sources make the latter category relatively more attractive. This trend is also visible in the scenario results of model comparison studies (Weyant, 2004; Ederhofer et al., 2006).

![Figure 3.21: Response index to assess priority setting in energy intensity reduction (more than 1.0) or in carbon intensity reduction (less than 1.0) for post TAR stabilization scenarios.](image)

Note: The panels give the development of the index for the years 2020, 2050, and 2100 (66, 77, and 59 scenarios respectively for which data on energy, GDP and carbon emissions were available. Data source: After Nakicenovic et al., 2006, and Hanaoka et al., 2006).

In addition to measures for reducing CO₂ emissions from energy and industry, emission reductions can also be achieved from other gasses and sources. Figure 3.22 illustrates the relative contribution of measures for achieving climate stabilization from three main sources: 1) CO₂ from energy and industry; 2) CO₂ from land-use change; and 3) the full basket of non-CO₂ emissions from all relevant sources. The Figure compares the contribution of these measures for achieving stabilization for a wide range of targets (between 2.6 and 5.3 W/m² by 2100) and baseline scenarios. An important conclusion across all stabilization levels and baseline scenarios is the central role of emissions reductions in the energy and industry sectors. All stabilization studies are consistent in that (independent of the baseline or target uncertainty) more than 65% of total emissions reduction would occur in this sector. The non-CO₂ gases and land-use related CO₂ emissions (including forests) are seen to contribute together up to 35% of total emissions reductions. As noted further above, however, the majority of recent studies indicate the relative importance of the latter two sectors for the cost-effectiveness of integrated multigas GHG abatement strategies (see also Section 3.3.5.4 on CO₂-only versus multigas mitigation and 3.3.5.5 on land-use).

The strongest divergence across the scenarios concerns the contribution of land-use related mitigation. The results range from negative contributions of land-use change to potential emissions savings of more than 1100 GtCO₂ over the course of the century (Figure 3.22). The primary reason for this is the large uncertainty with respect to future competition for land between dedicated bio-energy plantations and potential gains from carbon savings in terrestrial sinks. Some scenarios, for exam-

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10 Most of the models have an aggregated representation of the forest sector comprising the joint effects of deforestation, afforestation and avoided deforestation.
An illustrative example for the further breakdown of mitigation options is shown in Figure 3.23. The figure shows stabilization scenarios for a range of targets (about 3 to 4.5 W/m²) based on four illustrative models (IMAGE, MESSAGE, AIM and IPAC) for which sufficient data were available. The scenarios share similar stabilization targets, but differ with respect to salient assumptions for technological change, long-term abatement potentials, as well as model methodology and structure. In addition, the scenarios are also based on different baseline scenarios. For example, cumulative baseline emissions over the course of the century range between 6000 GtCO₂-eq. in MESSAGE and IPAC scenarios to more than 7000 GtCO₂-eq. in the IMAGE and AIM scenarios. The primary energy mix of the baseline as well as the mitigation scenarios is shown in Figure 3.24.

It should be noted that the figure shows reduction on top of the baseline (e.g. other renewables may already have a large baseline contribution). Above all, figure 3.23 illustrates the importance of a wide portfolio of reduction measures, with many different measures categories showing contributions of more than a few hundred GtCO₂ over the course of the century. In terms of the contribution of different options, there is agreement for some options, while there is disagreement for others. Among the category types that have a large potential over the long term (2000-2100) in at least one model are energy conservation, carbon capture and storage, renewables, nuclear and non-CO₂ gases. These options could thus constitute an important part of the mitigation portfolio. However, the difference between the model also emphasizes the impact of different assumptions and the associated uncertainty (e.g. for renewables, results can vary strongly depending on whether they are already used in the baseline, and how this category competes against other zero or low emission options in the power sector such as nuclear and CCS). The figure also illustrates that limitations of the mitigation portfolio with respect to CCS or forest sinks (AIM and IPAC) would lead to relatively higher contributions of other options, in particular nuclear (IPAC) and renewables (AIM).
Figure 3.23 also illustrates the increase of emissions reductions necessary to strengthen the target from 4.5 to about 3-3.6 W/m$^2$. Most of the mitigation options increase their contribution significantly by up to a factor of more than two. This effect is particularly strong over the short term (2000-2030), indicating the need of early abatement for meeting stringent stabilization targets. Another important conclusion from the figure is that CCS and forest sink options are playing a relatively modest role in the short-term mitigation portfolio, particularly for the intermediate stabilization target (4.5 W/m2). The results thus indicate that the wide-spread deployment of these options might require relatively longer time compared to the other options and also relatively higher carbon prices (see also Figure 3.24 on increasing carbon prices over time).

As noted above, assumptions with regards to the baseline can have significant implications for the contribution of individual mitigation options for achieving stabilization. Figure 3.24 clearly shows that the baseline assumptions of the four models differ, and that these differences play a role in explaining some of the results. For instance, the MESSAGE model already includes a large amount of renewables in its baseline and further expansion is relatively costly. Nevertheless, also some common trends among the models may be observed. First of all, in almost all cases a clear reduction in primary energy use can be seen. Second, in all models coal use is significantly reduced under the climate policy scenarios compared to the baseline. It should be noted that in those models, which consider CCS, the remaining fossil fuel use is mostly in combination with carbon capture and storage. In 2030, oil use is only modestly reduced by climate policies – and the same is the case for natural gas use in all models except MESSAGE. In 2100, both oil and gas are reduced compared to baseline in most models. Finally, in all models renewable energy and nuclear power increases – although the distribution across these two options differs.

Figure 3.23: Cumulative emissions reductions for alternative mitigation measures for 2000 to 2030 (left-hand panel) and for 2000-2100 (right-hand panel).

Notes: The figure shows scenarios from four illustrative models (AIM, IMAGE, IPAC and MESSAGE) aiming at the stabilization of radiative forcing at low (3-3.6 W/m2) and intermediate levels (4.5 W/m2) respectively. Dark bars denote reductions for a target of 4.5 W/m2 and light bars the additional reductions to achieve 3-3.6 W/m2. Note that some models do not consider mitigation through forest sink enhancement (AIM and IPAC) or CCS (AIM). Data source: Van Vuuren et al. (2007); Riahi et al. (2006); Hijioka, et al. (2006); Masui et al. (2006); Jiang et al. (2006).

Note that the low stabilization scenario for MESSAGE indicates an increase of primary energy use, because of massive deployment of CCS (from both bioenergy and fossil fuels). The energy penalty associated with the large-scale use of CCS leads to a relatively less efficient energy system, where primary energy needs become higher although net demand at the end-use level (energy services) has decreased similarly as in the low stabilization scenarios (3-3.6 W/m2) of the other models.
Figure 3.24: Primary energy mix for the year 2030 and 2100. Illustrative scenarios aiming at the stabilization of radiative forcing at low (3-3.6 W/m$^2$) and intermediate levels (4.5 W/m$^2$) respectively. For the corresponding contribution of individual mitigation measures in (in GtCO$_2$) see also Figure 3.23.

3.3.5.3 Stabilization costs

Models use different metrics to report the costs of emission reductions. Top-down general equilibrium models tend to report GDP losses, while system-engineering partial equilibrium models usually report the increase of energy system costs or the net present value (NPV) of the abatement costs. A common cost indicator is also the marginal cost/price of emissions reduction (US$/tC or US$/tCO$_2$).

Figure 3.25 shows the relationship between stabilization targets and alternative measures of mitigation costs comprising of GDP losses, net present value of abatement, and carbon price in terms of US$/tCO$_2$-eq.

It is important to note that for the following reported cost estimates, the vast majority of the models assume transparent markets, no transaction costs, and thus perfect implementation of policy measures throughout the 21$^{st}$ century, leading to the universal adoption of cost-effective mitigation measures, such as e.g., carbon taxes or universal cap and trade programs. These assumptions result generally in equal carbon prices across all regions and countries equivalent to global, least-cost estimates. Relaxation of these modeling assumptions, alone or in combination, e.g., mitigation only in Annex I countries, no emissions trading, or CO$_2$-only mitigation, will lead to an appreciable increase in all of the cost categories.

The gray shaded area in Figure 3.25 illustrates the 10-90$^{th}$ percentile of the mitigation cost ranges of recent studies including TAR. The area includes only those recent scenarios in the literature that report cost estimates based on a comprehensive mitigation analysis, defined as those which have a sufficiently wide portfolio of mitigation measures. The selection was made on a case by case basis for each scenario considered in this assessment. In addition, the figure shows also results from selected illustrative studies (coloured lines). These studies report costs for a range of stabilization targets and are representative for the overall cost dynamics of the full set of scenarios. They show

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12 The assessment of mitigation costs excludes stabilization scenarios that assume major limitation of the mitigation portfolio. For example, our assessment of costs does not include stabilization scenarios that exclude non-CO$_2$ mitigation options for achieving multi-gas targets (for cost implications of CO$_2$-only mitigation see also Section 3.3.5.4). The assessment nevertheless includes CO$_2$ stabilization scenarios that focus on single-gas stabilization of CO$_2$ concentrations. For achieving comparability of multigas and CO$_2$ stabilization scenarios, the relationship between the stabilization metrics given in Figure 3.16 is used.
cases with high, intermediate and low cost estimates (sometimes exceeding the $80^{th}$ (i.e., $10^{th}$-$90^{th}$) percentile range on the upper and lower bounds of the grey shaded area). The colour-coding is used to distinguish between individual mitigation studies, which are based on similar baseline assumptions. Generally, mitigation costs (for comparable stabilization targets) are higher from baseline scenarios with relatively high baseline emissions (brown and red lines). By the same token, intermediate or low baseline assumptions result in relatively lower cost estimates (blue and green lines).
a) Selected studies reporting GDP losses

<table>
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<th>GDP losses in 2030 (percent per year)</th>
<th>A1</th>
<th>A2</th>
<th>B</th>
<th>C</th>
<th>D</th>
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b) Selected studies reporting abatement costs (NPV)

<table>
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c) Selected studies reporting carbon prices

Figure 3.25: Relationship between the cost of mitigation and long-term stabilization targets (radiative forcing compared to pre-industrial level, W/m² and CO₂-eq. concentrations)

Notes: Panels give costs measured as % loss of GDP (a), net present value of cumulative abatement costs (b), and carbon price (c). Left-hand panels give costs for 2030, middle panel for 2050, and right-hand panel for 2100 respectively. Individual coloured lines denote selected studies with representative cost dynamics from very high to very low cost estimates. Scenarios from models sharing similar baseline assumptions are shown in the same colour. The grey shaded range represents the 80th percentile of TAR and post-TAR scenarios. NPV calculations are based on a discount rate of 5%. Solid lines show representative scenarios considering all radiatively active gases. CO₂ stabilization scenarios are added based on the relationship between CO₂ concentration and the radiative forcing targets given in Figure 3.16. Dashed lines represent multigas scenarios where the target is defined by the six Kyoto gases (other multigas scenarios consider all radiatively active gases).

Data sources: CCSP scenarios (USCCSP, 2006); IMCP scenarios (Edenhofer et al., 2006); Post-SRES (PS) scenarios (Morita et al., 2001); Azar et al., 2006, Riahi et al., 2006; Van Vuuren et al., 2007.
Figure 3.25a shows that the majority of studies find GDP losses increase with the stringency of the target even though there is considerable uncertainty with respect to the range of losses. Barker et al. (2006) found that, after allowing for baseline emissions, the differences can be explained by: (1) the spread of assumptions in modeling induced technical change, (2) the use of revenues from taxes and permit auctions, (3) the use of flexibility mechanisms, i.e., emissions trading, multi-gas mitigation, and banking, (4) the use of backstop technologies, (5) allowing for climate policy related co-benefits, and (6) other specific modeling assumptions. Weyant (2000) lists similar factors but also includes the number and type of technologies covered, and the possible substitution between costs factors (elasticities). A limited set of studies find negative GDP losses (economic gains) which arise from the assumption that a model’s baseline is assumed to be a non-optimal pathway and incorporates market imperfections. In these models, climate policies steer economies in the direction of reducing these imperfections, e.g., by promoting more investment into research and development and thus achieving higher productivity, promoting higher employment rates, or removing distortionary taxes.

The left-hand side panel of Figure 3.25a shows that for 2030, GDP losses in the vast majority of the studies (more than 90% of the scenarios) are generally below 1% for the target categories D and E. Also in the majority of the category B and C scenarios (70% of the scenarios) GDP losses are below 1%. It is important to note though that for categories B and C costs are on average higher, and show a wider range than those for D and E. For instance, for category C the interval lying between the 10th and 90th percentile varies from about 0.6% gain to about 1.2% loss. For category B, this range is shifted upwards (0 to 2.5%). This is also indicated by the median GDP losses by 2030, which increases from below 0.2% for categories D and E to about 0.2% for the category C scenarios and to about 0.6% for category B scenarios.

GDP losses by 2050 (middle panel of Figure 3.25a) are comparatively higher than the estimates for 2030. E.g., for category C scenarios the range is -1 to 2% GDP loss compared to baseline (median 0.5%) and for category B scenarios the range is from slightly negative to 4% (median 1.3%). The Stern review (2006), looking at the costs of stabilization in 2050 for a comparable category (500-550 CO2-eq.) found a similar range between -2 and +5%. For the studies that also explore different baselines (in addition to multiple stabilization levels), Figure 3.25a also shows that high emission baselines (e.g. high SRES-A1 or A2 baselines) tend to lead to higher costs. The uncertainty range across the models, however, is at least of a similar magnitude. Generally, models that combine assumptions of very slow or incremental technological change with high baseline emissions (e.g. IGSM-CCSP) tend to show the relatively highest costs (Figure 3.25a).

Finally, the most right-hand side panel of Figure 3.25a shows that GDP losses show a bigger spread and tend to be somewhat higher by 2100. GDP losses are between 0.3 and 3% for category D scenarios and -1.6 to about 5% for category C scenarios. Highest costs are given by category B (from slightly negative costs to 6.5%). The sample size for category A1 is not large enough for a statistical analysis. Similarly for category A2 scenarios the range is not shown as the A2 stabilization scenarios are predominantly based on low or intermediate baselines, and thus the resulting range would not be comparable to those from the other stabilization categories. Individual studies indicate though that costs become higher for more stringent targets (see e.g., studies highlighted in green and blue for the lowest stabilization categories in Figure 3.25a).

The results for the net present value of cumulative abatement costs show a similar picture (Figure 3.25b). However, given the fact that abatement costs only capture direct costs, this cost estimate is

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13 If not otherwise mentioned, the discussion of the cost ranges (Figure 3.25) refers to the 80th percentile of the TAR and Post-TAR scenario distribution (see the grey area in Figure 3.25).
by definition more certain. The interval from the 10\textsuperscript{th} to the 90\textsuperscript{th} percentile in 2100 is from nearly zero to about 11 trillion US$. The highest level corresponds to around 2-3\% of the NPV of global GDP over the same period. Again, on the basis of comparison across models it can be seen that costs depend both on the stabilization level and baseline emissions. In general, the spread of costs for each stabilization category seems to be of similar order as the differences across stabilization scenarios from different baselines. In 2030, the interval covering 80\% of the NPV estimates is from around 0-0.3 trillion for category C scenarios. The majority of the more stringent (category B) scenarios range between 0.2 to about 1.6 trillion. In 2050, typical numbers for category C are around 0.1 - 1.2 trillion US$ and category B this is 1 – 5 trillion (or below about 1\% of the NPV of GDP).

By 2100 the NPV estimates increase further with the range up to 5 trillion for category C scenarios and up to 11 trillion for category B scenarios respectively. The results of these studies published since TAR are consistent with the numbers presented in TAR, although the new studies extend results to substantially lower stabilization levels.

Finally, a similar trend is found for carbon price estimates. In 2030, typical carbon prices across the range of models and baselines for a 4.5 W/m\textsuperscript{2} stabilisation target (category C) range from around 1 – 24US$/tCO\textsubscript{2} (80\% of estimates), with the median of about 11US$/tCO\textsubscript{2}. For category B, the corresponding prices are somewhat higher and range from 18 - 79US$/tCO\textsubscript{2} (with the median of the scenarios around 45 US$/tCO\textsubscript{2}). Most individual studies for the most stringent category cluster around prices of about 100 US$/tCO\textsubscript{2}. Carbon prices by 2050 are comparatively higher than those in 2030. For example, costs of category C scenarios by 2050 range between 5 and 65 US$/tCO\textsubscript{2} and those for category B between 30 and 155US$/tCO\textsubscript{2}. Carbon prices in 2100 vary over a much wider range – mostly reflecting uncertainty in baseline emissions and technology development. For the medium target of 4.5 W/m\textsuperscript{2}, typical carbon prices in 2100 range from 25 – 200 US$/tCO\textsubscript{2} (80\% of estimates). This is primarily a consequence of the nature of this metric that often represents costs at the margin. Costs tend to slowly increase for more stringent targets – with a range between the 10\textsuperscript{th} and 90\textsuperscript{th} percentile of more than 35 to about 350 US$/tCO\textsubscript{2} for category B.

3.3.5.4 The role of non-CO\textsubscript{2} GHGs

As also illustrated by the scenario assessment in the previous sections, more and more attention has been paid since TAR to incorporating non-CO\textsubscript{2} gases into climate mitigation and stabilization analyses. As a result, there is now a body of literature (see e.g., van Vuuren et al. 2006-b, de la Chesnaye and Weyant, 2006, and de la Chesnaye et al. 2007) showing that mitigation costs for these sectors can be lower than for energy-related CO\textsubscript{2} sectors. As a result, 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\textsubscript{2} is the only GHG directly mitigated. These cost savings can be especially important where carbon dioxide is not the dominant gas, on a percentage basis, for a particular economic sector and even for a particular region. While the previous sections have focused on the joint assessment of CO\textsubscript{2} and multigas mitigation scenarios, this section is exploring the specific role of non-CO\textsubscript{2} emitting sectors.

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\footnote{NPV calculations are based on carbon tax projections of the scenarios, using a discount rate of 5\%, and assuming that the average cost of abatement would be half the marginal price of carbon. Some studies report abatement costs themselves, but for consistency this data were not used. The assumption of using half the marginal price of carbon results in a slight overestimation.}

\footnote{Note that the scenarios of the lowest stabilization categories (A1 and A2) are mainly based on intermediate and low baseline scenarios.}

\footnote{Note that the multigas stabilization scenarios, which consider only CO\textsubscript{2} abatement options (discussed in this section), are not considered in the overall mitigation cost assessment of Section 3.3.5.3.}
A number of parallel numerical experiments have been carried out by the Energy Modeling Forum (EMF-21, de la Chesnaye and Weyant, 2006). The overall conclusion is that economic benefits of multigas strategies are robust across all models. This is even so despite the fact that in the study different methods were used to compare the relative contribution of these gases in climate forcing (see 3.3.4.1). The EMF-21 study specifically focused on a comparison of stabilization scenarios aiming for 4.5 W/m$^2$ compared to pre-industrial levels. There were two cases 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 costs-effective approaches using full ‘what’ flexibility. In the CO$_2$-only mitigation scenario, all models significantly reduced CO$_2$ emissions, on average by about 75% in 2100 compared to baseline. Models still indicated some emission reductions for CH$_4$ and N$_2$O as a result of systemic changes in the energy system. Emissions of CH$_4$ were reduced by about 20% and N$_2$O by about 10% (Figure 3.26).
Figure 3.26: Reduction of emissions in the CO$_2$-only versus multi-gas strategies.
Source: de la Chesnaye and Weyant (2006) (see also van Vuuren et al., 2006-b)

In the multigas mitigation scenario, all models found that an appreciable percentage 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 75% to 67%. This percentage is still rather high, caused by the large share of CO$_2$ in total emissions (on average, 60% in 2100) and partly due to exhaustion of reduction options for...
the of non-CO₂ gases. The reductions of CH₄ across the different models averages around 50%, with remaining emissions coming from sources for which no reduction options were identified, such as CH₄ emissions from enteric fermentation. For N₂O, the increased reduction in the multi-gas strategy is not as large as for CH₄ (almost 40%). The main reason is that the identified potential for emission reductions for the main sources of N₂O emissions, fertilizer use and animal manure, is still limited. Finally, for the fluorinated gases, high reduction rates (about 75%) are found across the different models.

Although the contributions of different gases change sharply over time, there is a considerable spread among the different models. Many models project relatively early reductions of both CH₄ and the fluorinated gases under the multi-gas case. However, the subset of models that does not use GWPs as the substitution metric for the relative contributions of the different gases to the overall target, but does assume inter-temporal optimization in minimizing abatement costs, do not start to reduce CH₄ emissions substantially until the end of the period. The increased flexibility of a multigas mitigation strategy is seen to have significant implications for the costs of stabilization across all models participating in the EMF-21. These scenarios concur that multigas mitigation is significantly cheaper than CO₂-only. The potential reductions of the GHG price ranges in the majority of the studies between 30 to 85% (See Figure 3.27).

![Figure 3.27: Reduction in GHG abatement price (% in multigas stabilization scenarios compared to CO₂ only cases. Ranges correspond to alternative scenarios for a stabilization target of 4.5 W/m².](image)

*Data source: de la Chesnaye and Weyant, 2006.*

Finally, the EMF-21 research also showed that for some sources of non-CO₂ gases, the identified reduction potential is still very limited (e.g. most agricultural sources for N₂O emissions). In particular for long-term scenarios (and more stringent targets) identifying how this potential may develop in time is a crucial research question. Attempts to estimate the maximum feasible reductions (and the development of potential over time) have been made in van Vuuren *et al.*, (2007).
3.3.5.5 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$_2$O), increase sequestration of atmospheric CO$_2$ into plant biomass and soils, and produce biomass fuel substitutes for fossil fuels (see Chapters 8, 9, and 4 of this volume for discussions of detailed land related mitigation alternatives). Available information before TAR suggested that land has the technical potential to sequester up to an additional 319 billion tonnes CO$_2$ (GtCO$_2$) by 2050 in global forests alone (Watson et al., 1995; Watson et al., 2000; IPCC, 2001b). In addition, current technologies are capable of substantially reducing CH$_4$ and N$_2$O emissions from agriculture (see Chapter 8). A number of global biomass energy potential assessments have also been conducted (see Berndes et al. 2003 for an overview).

The explicit modeling of land based climate change mitigation in long-term global scenarios is relatively new and rapidly developing. As a result, assessment of the long-term role of global land based mitigation was not formally addressed by the Special Report on Land use, Land-use Change, and Forestry (Watson et al., 2000) or the TAR. This section assesses the modeling of land in long-term climate stabilization and the relationship to detailed global forestry mitigation estimates from partial equilibrium sectoral models that model 100-year carbon price trajectories.

Development of, among other things, global sectoral land mitigation models (e.g., Sohngen and Sedjo, 2006), bottom-up agricultural mitigation costs for specific technologies (e.g., USEPA, 2006b), and biomass technical potential studies (e.g., Hoogwijk et al., 2005) has facilitated the formal incorporation of land mitigation in long-term integrated assessment of climate change stabilization strategies. Hoogwijk et al. (2005), for example, estimated the potential of abandoned agricultural lands for providing biomass for primary energy demand and identified the technical biomass supply limits of this land type (e.g., under the SRES A2 scenario, abandoned agricultural lands could provide for 20% of 2001 total energy demand). Sands and Leimbach (2003) were one of the first to explicitly explore land based mitigation in stabilization, suggesting that the total cost of stabilization could be reduced by including land strategies in the set of eligible mitigation options (energy crops in this case). The Energy Modelling Forum Study-21 (EMF-21, de la Chesnaye and Weyant, 2006) was the first coordinated stabilization modeling effort to include an explicit evaluation of the relative role of land in stabilization; however, only a few models participated. Building on their EMF-21 efforts, some modeling teams have also generated even more recent stabilization scenarios with revised land modeling. The studies are conspicuously different in the specifics of their modelling of land and land-based mitigation (Rose et al., 2007). Differences in the types of land considered, emissions sources, and mitigation alternatives and implementation imply different opportunities and opportunity costs for land related mitigation; and, therefore, different outcomes.

Four of the modelling teams in the EMF-21 study directly explored the question of the cost-effectiveness of including land based mitigation in stabilization solutions and found that including these options (both non-CO$_2$ and CO$_2$) provided greater flexibility and was cost-effective for stabilizing radiative forcing at 4.5 W/m$^2$ (Kurosawa, 2006; van Vuuren et al., 2006-a; Rao and Riahi, 2006; Jakeman and Fisher, 2006). Jakeman and Fisher, for example, 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% at 2050 (3.4 trillion US$ in 2000 dollars), versus losses of around 7.1% (10.6 trillion US$) and 3.3% (4.9 trillion US$) for the CO$_2$-only and multi-gas scenarios respec-

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17 Most of the assessments are done with large regional spatial resolutions; exceptions are Fischer and Schrattenholzer (2001), Sorensen (1999), and Hoogwijk et al. (2005).
tively. Unfortunately, none of the EMF-21 papers isolated the GDP effects associated with biomass fuel substitution or agricultural non-CO$_2$ abatement. However, given agriculture’s small estimated share of total abatement (discussed below), the GDP savings associated with agricultural non-CO$_2$ abatement could be expected to be modest overall, though potentially strategically significant to the dynamics of mitigation portfolios. Biomass, on the other hand, may have a substantial abatement role and therefore a large effect on the economic cost of stabilisation. Notably, strategies for increasing cropland soil carbon have not been incorporated to date into this class of models (see Chapter 8 for an estimate of the near-term potential for enhancing agricultural soil carbon).

Figure 3.28 presents the projected mitigation from forestry, agriculture, and biomass for the EMF-21 4.5 W/m$^2$ stabilisation scenarios, as well as additional scenarios produced by the MESSAGE and IMAGE models—an approximate 3 W/m$^2$ scenario from Rao and Riahi (2006), a 4.5 W/m$^2$ scenario from Riahi et al. (2006), and approximately 4.5, 3.7, and 2.9 W/m$^2$ scenarios from van Vuuren et al. (2007) (see Rose et al., 2007, for a synthesis). While there are clearly different land based mitigation pathways being taken across models for the same stabilisation target and across targets with the same model and assumptions, some general observations can be made. First, forestry, agriculture, and biomass are called upon to provide significant cost-effective mitigation contributions (Rose et al., 2007). Over the near-term (2000-2030), forest, agriculture, and biomass together could account for cumulative abatement of 10 to 65 GtCO$_2$-eq - 15 to 60% of the total abatement considered by the available studies, with forest and agricultural non-CO$_2$ abatement providing at least three quarters of total land abatement.18 Over the entire century (2000-2100), cumulative land-based abatement of approximately 345 to 1260 GtCO$_2$-eq is estimated to be cost-effective, accounting for 15 to 40% of total cumulative abatement. Forestry, agriculture, and biomass abatement levels are each projected to grow annually with relatively stable annual increases in agricultural mitigation and gradual deployment of biomass mitigation that accelerates dramatically in the last half of the century to become the dominant land mitigation strategy.

Figures 3.28 and 3.29 show that additional land-based abatement is expected to be cost-effective with tighter stabilization targets and/or higher baseline emissions (e.g., see the IMAGE 2.3 results for various stabilisation targets and the MESSAGE 4.5 W/m$^2$ stabilisation results with B2 (EMF-21) and A2r baselines). Biomass is largely responsible for the additional abatement; however, agricultural and forestry abatement are also expected to increase. How they might increase is model and time dependent. In general, the overall mitigation role of agricultural abatement of rice methane and livestock methane and nitrous oxide (enteric and manure) and soil nitrous oxide is projected to be modest throughout the time horizon, with some suggestion of increased importance in early decades.

However, there are substantial uncertainties. There is little agreement about the magnitudes of abatement (Figures 3.28 and 3.29). The scenarios disagree about the role of agricultural strategies targeting CH$_4$ versus N$_2$O as well as the timing and annual growth of forestry abatement, some scenarios suggesting substantial early deployment of forest abatement, while others suggesting gradual annual growth or increasing annual growth.

18 The high percentage arises because some scenarios project that the required overall abatement from 2000 to 2030 is modest, and forestry and agricultural abatement options cost-effectively provide the majority of abatement.
Figure 3.28: Cost-effective agriculture, forest, and commercial biomass annual greenhouse gas emissions abatement from baselines from various 2100 stabilisation scenarios (note y-axis’ have different ranges)

Notes: The color of the line indicates the 2100 stabilisation target modeled: green < 3.25 W/m² (< 420 CO₂ concentration, < 510 CO₂-eq concentration), pink 3.25 – 4 (420 – 490, 510 – 590), and dark blue 4 – 5 (490 – 570, 590 – 710). The IMAGE-EMF21 and IMAGE 2.3 forest results are net of deforestation carbon loses induced by bioenergy crop extensification. These carbon loses are accounted for under forestry by the other scenarios. The MESSAGE-EMF21 results are from the sensitivity analysis of Rao and Riahi (2006). The GTEM-EMF21 scenarios ran through 2050 and the GTEM agriculture mitigation results include fossil fuel emissions reductions in agriculture (5-7% of the annual agricultural abatement). Scenario references: IMAGE-EMF21 (van Vuuren et al., 2006-a); MESSAGE-EMF21 (Rao and Riahi, 2006); MESSAGE-A2r (Riahi et al., 2006); GRAPE-EMF21 (Kurosawa, 2006); GTEM-EMF21 (Jakeman and Fisher, 2006); and IMAGE 2.3 (van Vuuren et al., 2007)

Source: Rose et al. (2007)
A number of the recent scenarios suggest that biomass energy alternatives could be essential for stabilization, especially as a mitigation strategy that combines the terrestrial sequestration mitigation benefits associated with Bio-energy CO$_2$ capture and storage (BECCS), where CO$_2$ emissions are captured during biomass energy combustion for storage in geologic formations (e.g., Rao and Riahi, 2006; Riahi et al., 2006; Kurosawa, 2006; van Vuuren et al., 2007; USCCSP, 2006). BECCS has also been suggested as a potential rapid response prevention strategy for abrupt climate change. Across stabilisation scenarios, absolute emissions reductions from biomass are projected to grow slowly in the first half of the century and then rapidly in the second half as new biomass processing and mitigation technologies become available. Figure 3.28 suggests biomass mitigation of up to 7 GtCO$_2$/yr in 2050 and 27 GtCO$_2$/yr in 2100 for cumulative abatement over the century of 115 to 749 GtCO$_2$ (Figure 3.29). Figure 3.30 presents the amount of commercial biomass primary energy utilized in various stabilisation scenarios. For example, in 2050, the additional biomass energy provides approximately 5 to 55 EJ for a 2100 stabilisation target of 4 to 5 W/m$^2$ and approximately 40 to 115 EJ for 3.25 to 4 W/m$^2$, accounting for about 0 to 10 and 5 to 20 per cent of 2050 total primary energy respectively (USCCSP, 2006; Rose et al., 2007). Over the century, the additional bio-energy accounts for 500 to 6,700 EJ for targets of 4 to 5 W/m$^2$ and 6,100 to 8,000 EJ for targets of 3.25 to 4 W/m$^2$ (1 to 9% and 9 to 13% of total primary energy respectively).

More biomass energy is supplied with tighter stabilisation targets, but how much is required for any particular target depends on the confluence of the many different modeling assumptions. Modeled demands for biomass include electric power and end use sectors (transportation, buildings, industry, and non energy uses). Current scenarios suggest that electric power is projected to dominate biomass demand in the initial decades and, in general, with less stringent stabilisation targets. Later in the century and for more stringent targets, transportation is projected to dominate biomass use. When biomass is combined with BECCS, biomass mitigation shifts to the power sector late in the century to take advantage of the net negative emissions from the combined abatement option, such
that BECCS could represent a significant share of cumulative biomass abatement over the century (e.g., 30 to 50% of total biomass abatement from MESSAGE in Figure 3.29).

**Figure 3.30:** Commercial biomass primary energy scenarios above baseline from various 2100 stabilization scenarios

Notes: The color of the line indicates the 2100 stabilisation target modeled: green < 3.25 W/m² (< 420 CO₂ concentration, < 510 CO₂-equivalent concentration), pink 3.25 – 4 (420 – 490, 510 – 590), dark blue 4 – 5 (490 – 570, 590 – 710), and light blue 5 – 6 (570 – 660, 710 – 860). Scenario references: IMAGE-EMF21 (van Vuuren et al., 2006-a); MESSAGE-EMF21 (Rao and Riahi, 2006); MESSAGE-A2r (Riahi et al., 2006); IMAGE 2.3 (van Vuuren et al., 2007); and IGSM and MiniCAM (USCCSP, 2006).

Source: Rose et al. (2007), USCCSP (2006)

To date, detailed analyses of large-scale biomass conversion with CO₂ capture and storage is scarce. As a result, current integrated assessment BECCS scenarios are based on a limited and uncertain understanding of the technology. In general, further research is necessary to characterize biomass’ long-term mitigation potential, especially in terms of land area and water requirements, constraints, and opportunity costs, infrastructure possibilities, cost estimates (collection, transportation, and processing), conversion and end-use technologies, and ecosystem externalities. In particular, present studies are relatively poor in representing land competition with food supply and timber production, which has a significant influence on the economic potential of bio-energy crops (an exception is Sands and Leimbach, 2003).

Terrestrial mitigation projections are expected to be regionally unique, while still linked across time and space by changes in global physical and economic forces. For example, Rao and Riahi (2006) offer intuitive results on the potential role of agricultural methane and nitrous oxide mitigation across industrialized and developing country groups, finding that agriculture is expected to be a larger share of the developing countries’ total mitigation portfolio; and, developing countries are likely to provide the vast majority of global agricultural mitigation. Some aggregate regional forest mitigation results also are discussed below. However, given the paucity of published regional results from integrated assessment models, it is currently not possible to assess the regional land-use abatement potential in stabilization. Future research should direct attention to this issue in order to more fully characterize mitigation potential.

In addition to the stabilization scenarios discussed thus far from integrated assessment and climate economic models, the literature includes long-term mitigation scenarios from global land sector economic models (e.g., Sohngen and Sedjo, 2006; Sathaye et al., 2006; Sands and Leimbach, 2003).
Therefore, a comparison is prudent. The sectoral models use exogenous carbon price paths to simulate different climate policies and assumptions. It is possible to compare the stabilisation and sectoral scenarios using these carbon price paths. Stabilisation (e.g., EMF-21, discussed above) and “optimal” (e.g., Sohngen and Mendelsohn, 2003) climate abatement policies suggest that carbon prices will rise over time.\(^{19}\) Table 3.6 compares the forest mitigation outcomes from stabilisation and sectoral scenarios that have similar carbon price trajectories (Rose et al., 2007).\(^{20}\) Rising carbon prices will provide incentives for additional forest area, longer rotations, and more intensive management to increase carbon storage. Higher effective energy prices might also encourage shorter rotations for joint production of forest bioenergy feedstocks.

Table 3.6 shows that the vast majority of forest mitigation is projected to occur in the second half of the century, with tropical regions in all but one scenario in Table 3.6 assuming a larger share of global forest sequestration/mitigation than temperate regions. The IMAGE results from EMF-21 are discussed separately below. Lower initial carbon prices shift early period mitigation to the temperate regions since, at that time, carbon incentives are inadequate for arresting deforestation. The sectoral models project that 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. The current stabilisation scenarios model more limited and aggregated forestry GHG abatement technologies that do not distinguish the detailed responses seen in the sectoral models.

The sectoral models, in particular, Sohngen and Sedjo, suggest substantially more mitigation in the second half of the century compared to the stabilisation scenarios. A number of factors are likely to be contributing to this deviation from the integrated assessment model results. First and foremost, is that Sohngen and Sedjo explicitly model future markets, which none of the integrated assessment models are currently capable of doing. Therefore, a low carbon price that is expected to increase rapidly results in a postponement of additional sequestration actions in Sohngen and Sedjo until the price (benefit) of sequestration is greater. Endogenously modeling forest biophysical and economic dynamics will be a significant future challenge for integrated assessment models. Conversely, the integrated assessment models may be producing a somewhat more muted forest sequestration response given the following: (i) their explicit consideration of competing mitigation alternatives across all sectors and regions, and, in some cases, land use alternatives; (ii) their more limited set of forest related abatement options, with all integrated assessment models modelling afforestation strategies, but only some considering avoided deforestation, and none modelling forest management options at this point; (iii) some integrated assessment models (including those in Table 3.6) sequentially allocate land, satisfying population food and feed demand growth requirements first, and (iv) climate feedbacks in integrated assessment models can lead to terrestrial carbon loses relative to the baseline.

\(^{19}\) Optimal is defined in economic terms as the equating of the marginal benefits and costs of abatement.

\(^{20}\) Rose et al. (2007) reports the carbon price paths from numerous stabilisation and sectoral mitigation scenarios.
Table 3.6: Cumulative forest carbon stock gains above baseline by 2020, 2050 and 2100 from long term global forestry and stabilisation scenarios (GtCO$_2$)

<table>
<thead>
<tr>
<th>Source and Scenario</th>
<th>Region</th>
<th>2020</th>
<th>2050</th>
<th>2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sathaye et al. (2006)</td>
<td>World</td>
<td>na</td>
<td>91.3</td>
<td>353.8</td>
</tr>
<tr>
<td></td>
<td>Temperate</td>
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<td>25.3</td>
<td>118.8</td>
</tr>
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<td></td>
<td>Tropics</td>
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<td>55.1</td>
<td>242.0</td>
</tr>
<tr>
<td>Sohngen and Sedjo (2006)</td>
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<td>0.0</td>
<td>22.7</td>
<td>537.5</td>
</tr>
<tr>
<td>original baseline</td>
<td>Temperate</td>
<td>3.3</td>
<td>8.1</td>
<td>207.9</td>
</tr>
<tr>
<td></td>
<td>Tropics</td>
<td>-3.3</td>
<td>14.7</td>
<td>329.6</td>
</tr>
<tr>
<td>Sohngen and Sedjo (2006)</td>
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<td>1.5</td>
<td>15.0</td>
<td>487.3</td>
</tr>
<tr>
<td>accelerated deforestation baseline</td>
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<td>12.1</td>
<td>212.7</td>
</tr>
<tr>
<td></td>
<td>Tropics</td>
<td>0.7</td>
<td>2.9</td>
<td>275.0</td>
</tr>
</tbody>
</table>

Stabilisation at 4.5 W/m$^2$ (~650 CO$_2$eq ppmv) by 2010

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Region</th>
<th>2020</th>
<th>2050</th>
<th>2100</th>
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<td>-13.4</td>
<td>10.4</td>
</tr>
<tr>
<td></td>
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<td>14.1</td>
<td>31.9</td>
<td>78.3</td>
</tr>
<tr>
<td></td>
<td>Tropics</td>
<td>-36.6</td>
<td>-45.3</td>
<td>-67.9</td>
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<tr>
<td>MESSAGE-EMF21*</td>
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<td>3.5</td>
<td>152.5</td>
</tr>
<tr>
<td></td>
<td>Temperate</td>
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<td>0.1</td>
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<td></td>
<td>Tropics</td>
<td>0.0</td>
<td>3.4</td>
<td>129.1</td>
</tr>
</tbody>
</table>

Source: Stabilisation data assembled from Rose et al. (2007)

Notes:
* Results based on the 4.5 W/m$^2$ MESSAGE scenario from the sensitivity analysis of Rao and Riahi (2006).

Temperate: North America, Western and Central Europe, Former Soviet Union, East Asia, Oceania, Japan
Tropics: Central America, South America, Sub-Saharan Africa, South Asia, Southeast Asia

na = data not available

The IMAGE results in Table 3.6 provide a dramatic illustration of the potential implications and importance of some of these counterbalancing effects. Despite the planting of additional forest plantations in the IMAGE scenario, net tropical forest carbon stocks decline relative to the baseline due to deforestation induced by bioenergy crop extensification, as well as reduced CO$_2$ fertilization that affects forest carbon uptake, especially in tropical forests, and decreases crop productivity, where the latter effect induces greater expansion of food crops onto fallow lands thereby displacing stored carbon.

In addition to reducing uncertainty about the magnitude and timing of land-based mitigation, biomass potential, and regional potential, there are 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. Of particular importance to climate stabilization are the albedo implications of land-use change, which can offset emissions reducing land-use change (Betts, 2000; Schaeffer et al., 2006), as well as the potential climate driven changes in forest disturbance frequency and intensity that could affect the effectiveness of forest mitigation strategies. Non-climate implications should also be considered. As shown in the Millennium 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).

A number of relevant key baseline land modelling challenges have already been discussed in Sections 3.2.1.3 and 3.2.2.2. Central to future long-term land mitigation modelling are improvements in the dynamic modelling of regional land use and land-use competition and mitigation cost estimates, as well as modelling of the implications of climate change for land-use and land mitigation opportunities. The total cost of any land based mitigation strategy should include the opportunity costs of land, which are dynamic and regionally unique functions of changing regional bio-physical and economic circumstances. In addition, the results presented in this section do not consider climate shifts that could dramatically alter land-use conditions, such as a permanent El-Nino-like state in tropical regions (Cox et al., 1999).

In summary, recent stabilisation studies have found that landuse mitigation options (both non-CO$_2$ and CO$_2$) provide cost-effective abatement flexibility in achieving 2100 stabilisation targets, on the order of 345 to 1260 GtCO$_2$-eq (15 to 40 per cent) of cumulative abatement over the century. In some scenarios, increased commercial biomass energy (solid and liquid fuel) is significant in stabilisation, providing 115 to 749 GtCO$_2$-eq (5 to 30 per cent) of cumulative abatement and 500 to 9,500 EJ of additional bio-energy above the baseline over the century (potentially 1 to 15 per cent of total primary energy), especially as a net negative emissions strategy that combines biomass energy with CO$_2$ capture and storage. Agriculture and forestry mitigation options are projected to be cost effective near- and long-term abatement strategies. Global forestry models project greater additional forest sequestration than found in stabilization scenarios, a result attributable in part to differences in the modelling of forest dynamics and general economic feedbacks. Overall, the explicit modeling of land based climate change mitigation in long-term global scenarios is relatively immature with significant opportunities for improving baseline and mitigation land use scenarios.

3.3.5.6 Air Pollutants, including co-benefits

Quantitative analysis on a global scale for the implications of climate mitigation for air pollutants such as SO$_2$, NO$_x$, CO, VOC, BC and OC, are relatively scarce. 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. Previous studies have focused on purely ancillary benefits to air pollution that accrue from a climate mitigation objective but recently there is a focus on integrating air quality and climate concerns, thus analyzing the co-benefits of such policies. Several recent reviews have summarized the issues related to such benefits (OECD 2000, OECD 2003). They cover absolute air pollutant emission reductions, monetary value of reduced pollution, the climatic impacts of such reductions and the improved health effects due to reduced pollution.

The magnitude of such benefits largely depends on the assumptions on future policies and technological change in the baseline against which they are measured, as discussed in Morgensten (2000). For example, Smith et al. (2005) and Rao et al. (2005) assume an overall growth in environmental awareness and formulation of new environmental policies with increased affluence in the baseline scenario and thus reduced air pollution even in absence of any climate policies. The pace of this trend differs significantly across pollutants and baseline scenarios and may or may not have an obvious effect on greenhouse gases. An added aspect of ancillary benefit measurement is the representation of technological options. Some emissions control technologies reduce both air pollutants and greenhouse gases, like selective catalytic reduction (SCR) on gas boilers that reduces not only NO$_x$, but also N$_2$O, CO and CH$_4$ (IPCC, 1997). But there are also examples where, at least in principle, emission control technologies aimed at a certain pollutant could increase emissions of other pollut-
ants. For example, the substitution of more fuel-efficient diesel engines for gasoline engines might lead to higher PM/black carbon emissions (Kupiainen and Klimont 2004). Thus estimating co-benefits of climate mitigation should include adequate sectoral representation of emission sources, a wide range of substitution possibilities, assumptions on technological change and a clear representation of current environmental legislation.

Only a few studies have explored the longer term ancillary benefits of climate policies. Alcamo (2002) and Mayerhofer et al. (2002) assess in detail the linkages between regional air pollution and climate change in Europe. They emphasize important co-benefits between climate policy and air pollution control but also indicate that depending on assumptions, air pollution policies in Europe will play a greater role in air pollutant reductions than climate policy. Smith and Wigley (2006) suggest that there will be a slight reduction in global sulfur aerosols as a result of long-term multi-gas climate stabilization. Rao et al. (2005) and Smith and Wigley (2006) find that climate policies can reduce cumulative BC and OC emissions by providing the impetus for adoption of cleaner fuels and advanced technologies. In addition, the inclusion of co-benefits for air pollution can have significant impacts on the cost effectiveness of both the climate policy and air pollution policy under consideration. Van Harmelen et al. (2002) find that to comply with agreed upon or future policies to reduce regional air pollution in Europe, mitigation costs are implied, but these are reduced by 50-70% for SO₂ and around 50% for NOₓ when combined with GHG policies. Similarly, in the shorter-term, Van Vuuren et al. (2006-c) find that for the Kyoto protocol, about half the costs of climate policy might be recovered from reduced air pollution control costs. The exact benefits, however, critically depend on how the Kyoto protocol is implemented.

The different spatial and temporal scale of greenhouse gases and air pollutants is a major difficulty in evaluating ancillary benefits. Swart et al. (2004) stress the need for new analytical bridges between these different spatial and temporal scales. Rypdal et al. (2005) suggests the possibility of including some local pollutants like CO and VOCs in global climate agreement with others like NOₓ and aerosols being regulated by regional agreements. It should be noted that some air pollutants like sulphate and carbonaceous aerosols exert radiative forcing and thus global warming but their contribution is uncertain. Smith and Wigley (2006) find that the attendant reduced aerosol cooling from sulphates can more than offset the reduction in warming that accrues from reduced GHGs. On the other hand, air pollutants such as NOₓ, CO and VOC act as indirect greenhouse gases having an influence for example via their impact on OH radicals and therefore the lifetime of direct greenhouse gases (e.g., methane and HFC). Further, the climatic effects of some pollutants like BC and OC aerosols remain unclear.

While there has been a lot of recent research in estimating co-benefits of joint GHG and air pollution policies, most current studies do not have a comprehensive treatment of co-benefits in terms of reduction costs and the related health and climate impacts in the long-term, thus indicating the need for more research in this area.

### 3.3.6 Characteristics of regional and national mitigation scenarios

Table 3.7 summarizes selected national mitigation scenarios. There are broadly two types of national scenarios with focus on climate mitigation. First are the scenarios that study mitigation options and related costs under a given national emissions cap and trade regime. Second are the national scenarios that focus on evaluation of climate mitigation measures and policies in the absence of specific emissions targets. The former type of analysis has been mainly undertaken in the studies in the European Union and Japan. The latter type has been explored in the United States, Canada and Japan. In addition, there is also an increasing body of literature, mainly in developing
countries, which analyses national GHG emissions in the context of domestic concerns such as energy security and environmental co-benefits. Many of these developing country analyses do not explicitly address emissions mitigation. In contrast to global studies, regional scenario analyses have focused on shorter time horizons, typically up to between 2030 and 2050.

A number of scenario studies have been conducted for various countries within Europe. These studies explore a wide range of emission caps, taking into account local circumstances and potentials for technology implementation. Many of these studies have used specific burden sharing allocation schemes like the contraction and convergence (C&C) approach for calculating allocation of worldwide emissions to estimate national emissions ceilings. The United Kingdom’s Energy White Paper (DTI, 2003) examined measures to achieve a 60% reduction in CO$_2$ emissions by 2050 as compared to the current level. Several studies have explored renewable energy options, for example, the possibility of expanding the share of renewable energy and the resulting prospects for clean hydrogen production from renewable energy sources in Germany (Deutscher Bundestag, 2002; Fischedick and Nitsch, 2002; Fischedick et al., 2005). A European study, the COOL project (Tuinstra et al., 2002; Treffers et al., 2005), has explored the possibilities of reducing emissions in the Netherlands by 80% in 2050 compared to 1990 levels. In France, the Inter Ministerial Task Force on Climate Change (MIES, 2004) has examined mitigation options that could lead to significant reductions in per capita emissions intensity. Savolainen et al. (2003) and Lehtila et al. (2005) have conducted a series of scenario analyses in order to assess technological potentials in Finland for a number of options including wind power, electricity saving possibilities in households and office appliances, and emission abatement of fluorinated GHGs.

Scenario studies in the United States have explored the implications of climate mitigation for energy security (Hanson et al., 2004). For example, Mintzer et al. (2003) developed a set of scenarios describing three divergent paths for US energy supply and use from 2000 through 2035. These scenarios were used for identification of key technologies, important energy policy decisions, and strategic investment choices that may enhance energy security, environmental protection, and economic development.

A wide range of scenario studies have also been conducted to estimate potential emissions reductions and associated costs for Japan. For example, Masui et al. (2006) developed a set of scenarios that explore the implications of severe emissions cut backs between 60 and 80% CO$_2$ by 2050 (compared to 1990). Another important study by Akimoto et al. (2004) evaluates the possibilities of introducing the carbon capture and storage (CCS) option and its economic implications for Japan.

National scenarios pertaining to developing countries such as China and India mainly analyze future emission trajectories under various scenarios that include considerations like economic growth, technology development, structure changes, globalization of world markets, and impacts of mitigation options. Unlike the scenarios developed for the European countries, most of the developing country scenarios do not specify limits on emissions (van Vuuren et al., 2003; Jiang and Hu, 2005). Chen (2005) shows that structural change can be a more important contributor than technology efficiency improvement for CO$_2$ reduction. The scenario construction for India pays specific attention to developing country dynamics underlying the multiple socio-economic transitions during the century, including demographic transitions (Shukla et al., 2006). Nair et al. (2003) studied potential shifts away from coal intensive baselines to the use of natural gas and renewables.
There are several country scenarios that consider drastic reduction of CO$_2$ emissions. In these studies, considering 60-80% reductions of CO$_2$ in 2050, rates of improvement of energy intensity and carbon intensity increase by about two to three times their historical levels (Kawase et al., 2006).

Table 3.8 summarizes scenarios with more than 40% CO$_2$ reductions from 2000 to 2050 in several developed countries. In addition, the table also includes some Chinese scenarios with deep cuts of CO$_2$ emissions compared to the reference cases. Physical indicators of the Chinese economy show that current efficiency is below the OECD average in most sectors, thus indicating a greater scope for improvement (Jiang et al., 2003). It should be noted that comparison of energy intensity of the Chinese economy on the basis of market exchanges rates to OECD averages suggests even larger differences, but this is misleading given the differences in purchasing power (PPP corrected energy intensity data give a somewhat better basis for comparison but still suffers from uncertainty about the data and different economic structures).

In the countries with low energy intensity levels in 2000 such as Japan, Germany and France, the scenarios specify solution for meeting long-term drastic reduction goals by carbon intensity improvement measures such as shifting to natural gas in the United Kingdom, renewable energy in the Netherlands, and CCS in certain scenarios in France, Germany, the United Kingdom and the United States. France has a scenario where CCS accounts for 100% of carbon intensity improvement. Most of the scenarios with drastic CO$_2$ reductions for the United States and the United Kingdom assume introduction of CCS.

The light yellow colored area in Table 3.8 shows the range of the global model results of EMF21 with the stabilization target of 4.5 W/m$^2$. Most country results show the requirement of larger improvement in carbon intensity during 2000 to 2050 compared to the global results. The results of scenario analysis since TAR show that energy intensity improvement is superior to carbon intensity reduction in the first half of the 21st century, but the carbon intensity reduction becomes more dominant in the latter half of the century (Hanaoka et al., 2006).
### Table 3.7: National scenarios with quantification up to 2050 and beyond

<table>
<thead>
<tr>
<th>Country</th>
<th>Author/Agency</th>
<th>Model</th>
<th>Time horizon</th>
<th>Target variables</th>
<th>Base year</th>
<th>Target of reduction to the value of the base year</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>Hanson et al. (2004)</td>
<td>AMIGA¹</td>
<td>2000-2050</td>
<td>-</td>
<td>2000</td>
<td>(about 44% in 2050)</td>
</tr>
<tr>
<td>India</td>
<td>Nair et al. (2003)</td>
<td>Integrated modeling framework¹,²</td>
<td>1995-2100</td>
<td>cumulative CO₂ emissions</td>
<td>550 ppm, 650 ppm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shukla et al. (2005)</td>
<td>ERB²</td>
<td>1990-2095</td>
<td>CO₂ emissions</td>
<td>550 ppm</td>
<td></td>
</tr>
<tr>
<td>China</td>
<td>Chen (2005)</td>
<td>MARKAL-MACRO²,³</td>
<td>2000-2050</td>
<td>CO₂ emissions reference</td>
<td>5%-45% in 2050</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Van Vuuren et al. (2003)</td>
<td>IMAGE/TIMER²,⁴</td>
<td>1995-2050</td>
<td>GHG emissions</td>
<td>1995</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Jiang et al. (2003)</td>
<td>IPAC-emission²,³</td>
<td>1990-2100</td>
<td>GHG emissions</td>
<td>1990</td>
<td>-</td>
</tr>
<tr>
<td>Netherlands</td>
<td>Tuinstra et al. (2002) [COOL]</td>
<td></td>
<td>1990-2050</td>
<td>GHG emissions</td>
<td>1990</td>
<td>80% in 2050</td>
</tr>
<tr>
<td>Germany</td>
<td>Deutscher Bundestag (2002)</td>
<td>WT², IER</td>
<td>2000-2050</td>
<td>CO₂ emissions</td>
<td>1990</td>
<td>80% in 2050</td>
</tr>
<tr>
<td>UK</td>
<td>Department of Trade and Industry[DTI] (2003)</td>
<td>MARKAL²</td>
<td>2000-2050</td>
<td>CO₂ emissions</td>
<td>2000</td>
<td>45%, 60%, 70% in 2050</td>
</tr>
<tr>
<td>France</td>
<td>Interministerial Task Force on Climate Change[MIES] (2004)</td>
<td>N.A.</td>
<td>2000-2050</td>
<td>CO₂ emissions</td>
<td>2000</td>
<td>0.5 tC/cap (70% in 2050)</td>
</tr>
<tr>
<td>Australia</td>
<td>Ahammad et al. (2006)</td>
<td>GTEM¹</td>
<td>2000-2050</td>
<td>GHG emissions</td>
<td>1990</td>
<td>50% in 2050</td>
</tr>
<tr>
<td>Japan</td>
<td>Japan LCS Project (2005)</td>
<td>AIM/Material¹ MENOCO³</td>
<td>2000-2050</td>
<td>CO₂ emissions</td>
<td>1990</td>
<td>60-80% in 2050</td>
</tr>
<tr>
<td></td>
<td>Masui et al. (2006)</td>
<td>AIM/Material¹</td>
<td>2000-2050</td>
<td>CO₂ emissions</td>
<td>1990</td>
<td>74% in 2050</td>
</tr>
<tr>
<td></td>
<td>Akimoto (2004)</td>
<td>Optimization model³</td>
<td>2000-2050</td>
<td>CO₂ emissions</td>
<td>2000</td>
<td>0.5% / yr (21% in 2050)</td>
</tr>
</tbody>
</table>
Table 3.8: Developed countries scenarios with more than 40% reduction as compared to 2000 emissions, and some Chinese scenarios: CO₂ emission changes from 2000 to 2050; Energy intensity and carbon intensity in 2000, and their changes from 2000 up to 2050
(A) CO₂ emission changes, energy intensity, and carbon intensity in 2000.

<table>
<thead>
<tr>
<th>Country</th>
<th>CO₂ emission change[%] (2000-2050)</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>-59.5</td>
</tr>
<tr>
<td>Japan</td>
<td>-31.9</td>
</tr>
<tr>
<td>Germany</td>
<td>-69.8</td>
</tr>
<tr>
<td>France</td>
<td>-69.8</td>
</tr>
<tr>
<td>UK</td>
<td>-69.8</td>
</tr>
<tr>
<td>USA</td>
<td>-65.7</td>
</tr>
</tbody>
</table>

Initial value (2000)

<table>
<thead>
<tr>
<th>Country</th>
<th>Energy intensity [toe/1000 95$(MER)]</th>
<th>Carbon intensity [tn CO₂/ktoe]</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>595</td>
<td>377.8</td>
</tr>
<tr>
<td>Japan</td>
<td>0.97</td>
<td>2.61</td>
</tr>
<tr>
<td>Germany</td>
<td>0.13</td>
<td>2.43</td>
</tr>
<tr>
<td>France</td>
<td>0.15</td>
<td>1.46</td>
</tr>
<tr>
<td>UK</td>
<td>0.18</td>
<td>2.26</td>
</tr>
<tr>
<td>USA</td>
<td>0.26</td>
<td>2.47</td>
</tr>
</tbody>
</table>

(B) Changes in energy intensity and carbon intensity

<table>
<thead>
<tr>
<th>Country</th>
<th>Energy intensity</th>
<th>CO₂ emission reduction factors</th>
<th>Carbon intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>-4.02</td>
<td>-2.47</td>
<td>-1.03</td>
</tr>
<tr>
<td>Japan</td>
<td>-2.82</td>
<td>-0.84</td>
<td>-1.87</td>
</tr>
<tr>
<td>Germany</td>
<td>2.83</td>
<td>-1.11</td>
<td>-2.73</td>
</tr>
<tr>
<td>France</td>
<td>-2.26</td>
<td>-1.33</td>
<td>-2.65</td>
</tr>
<tr>
<td>UK</td>
<td>-5.05</td>
<td>-2.82</td>
<td>-2.39</td>
</tr>
<tr>
<td>USA</td>
<td>-2.70</td>
<td>-2.20</td>
<td>-1.29</td>
</tr>
</tbody>
</table>


3.3.6.1 Costs of mitigation in regional and country scenarios

Figure 3.31 shows the relationship between carbon prices and the CO₂ mitigation rates from the baseline in 2050 in some major countries and regions such as the United States, Japan, EU-15, India, China, Former Soviet Union (FSU) and Eastern Europe, taken from the literature since TAR (Hanaoka et al., 2006). In the developing countries there are many scenarios where relatively high CO₂ reductions are projected even with low carbon prices. With high prices in the range of 100-150 2000 US$/tCO₂, more CO₂ reductions are expected in China and India than in developed countries when the same level of carbon price is applied.
Figure 3.31: Relation between carbon prices and CO₂ reduction from baseline in 2050 in selected countries taken from the literature published since TAR.
Note: The red box shows the range between the 25th to 75th percentile of the scenarios for each price range, i.e. the price range from 0 to 50, from 50 to 100, and from 100 - 150 US$2000/tCO₂ respectively. The red-dotted line indicates the median for each cost range.

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

Technology is among the central driving forces of GHG emissions. It is 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 of GHGs (see Ch. 2, Section 2.8.1 that assesses the role of technology in climate change mitigation including long-term emissions and stabilization scenarios).

The ways in which technology reduces future GHG emissions in long-term emission scenarios include:
- Improving technology efficiencies and thereby reducing emissions per unit service (output). These measures are enhanced when complemented by energy conservation and rational use of energy;
- Replacing carbon 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 cycle 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 could be applied at some time in the future in conjunction with essentially all electricity generation technologies, many other energy conversion technologies and energy-intensive processes using fossil energy sources as well as biomass (in which case it corresponds to net carbon removal from the atmosphere);
Introducing carbon free renewable energy sources ranging from a larger role of hydro and wind power, photovoltaics and solar thermal power plants, modern biomass (that can be carbon neutral resulting in zero net carbon emissions) and other advanced renewable technologies;

- Enhancing the role of nuclear power as another carbon free source of energy. This would require a further increase of the nuclear share in global energy, dependent on the development of ‘inherently’ safe reactors and fuel cycles, resolution of the technical issues associated with long-term storage of fissile materials and improvement of national and international non-proliferation agreements.

- New technology configurations and systems, e.g. hydrogen as a carbon free carrier to complement electricity, fuel cells and new storage technologies.

- Reducing GHG and CO\(_2\) emissions from agriculture and land use in general critically depends on diffusion of new technologies and practices that could include less fertilizer intensive production and improvement of tillage and livestock management.

Virtually all scenarios assume that technological and structural changes occur during this century leading to relative reduction of emissions compared to the hypothetical case of attempting to ‘keep’ emissions intensities of GDP and structure the same as today (see Ch. 2, Section 2.8.1.1 that discusses the role of technology in baseline scenarios). Figure 3.32 shows such a hypothetical range of cumulative emissions under the assumption of ‘freezing’ technology and structural change in all scenarios at current levels, but letting populations change and economies develop as assumed in the original scenarios (Nakicenovic et al., 2006). To show this, the energy intensity of GDP and the carbon intensity of energy are kept constant. The bars in the figure indicate the central tendencies of the scenarios in the literature by giving the cumulative emissions ranges between the 25\(^{th}\) and the 75\(^{th}\) percentile of the scenarios in the scenario database.\(^{21}\) The hypothetical cumulative emissions (without technology and structural change) range from 2427 (25\(^{th}\) percentile) to 3133 (75\(^{th}\) percentile) with a median of 2804 GtC by 2100.

The next bar in Figure 3.32 shows cumulative emissions by keeping carbon intensity of energy constant while allowing energy intensity of GDP to evolve as originally specified in the underlying scenarios. This in itself reduces the cumulative emissions substantively, by more than 40 to almost 50% (75\(^{th}\) and 25\(^{th}\) percentiles, respectively). Thus, structural economic changes and more efficient use of energy lead to significant reductions of energy requirements across the scenarios as incorporated in the baselines indicating that the baseline already includes vigorous carbon saving. In other words, this means that many new technologies and changes that lead to lower relative emissions are assumed in the baseline. Any mitigation measures and policies need to go beyond these baseline assumptions.

The next bar in Figure 3.32 also allows carbon intensities of energy to change as originally assumed in the underlying scenarios. Again, the baseline assumptions lead to further and substantial reductions of cumulative emissions, by some 13 to more than 20% (25\(^{th}\) and 75\(^{th}\) percentile, respectively), or less than half of emissions, as compared to the case of no improvement of energy or carbon intensities. This results in the original cumulative emissions as specified by reference scenarios in the literature, from 1085 (25\(^{th}\) percentile) to 1460 (75\(^{th}\) percentile) with a median of 1268 GtC by 2100. It should be noted that this range is for the 25\(^{th}\) to the 75\(^{th}\) percentile only. In

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\(^{21}\) The outliers, above the 75\(^{th}\) and below the 25\(^{th}\) percentile are discussed in more detail in the subsequent sections.
contrast, the full range of cumulative emissions across 56 scenarios in the database is from 566 to 1974 GtC.\textsuperscript{22}

The next and final step is to compare the cumulative emissions across baseline scenarios with those in the mitigation and stabilization variants of the same scenarios. Figure 3.32 shows in the last bar yet another significant reduction of future cumulative emissions from 728 to 1032 (corresponding to the 25\textsuperscript{th} to the 75\textsuperscript{th} percentile of the full scenario range) with a median of 847 GtC by 2100. This corresponds to about 70% emissions reduction across mitigation scenarios compared to the hypothetical case of no changes in energy and carbon intensities and still a large, or about a 30% reduction compared to the respective baseline scenarios.\textsuperscript{23}

![Figure 3.32: Median, 25\textsuperscript{th} and 75\textsuperscript{th} percentile of global cumulative carbon emissions by 2100 in the scenarios developed since 2001.](image)

<table>
<thead>
<tr>
<th>GtCO2</th>
<th>frozen technology</th>
<th>frozen energy intensity</th>
<th>baseline</th>
<th>intervention</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>25th percentile</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>14000</td>
<td>75th percentile</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: The range labeled “frozen technology” refers to hypothetical futures without improvement in energy and carbon intensities in the scenarios, the range labeled “frozen energy intensity” to hypothetical futures where only carbon intensity of energy is kept constant while energy intensity of GDP is left the same as originally assumed in scenarios, the range labeled CO\textsubscript{2} baseline are the 83 baseline scenarios in the database, while the region labeled CO\textsubscript{2} intervention includes 211 mitigation and/or stabilization scenarios.

Source: After Nakicenovic et al. (2006)

This illustrates the importance of technology and structural changes both in reference and mitigation scenarios. However, this is an aggregated illustration across all scenarios and different mitigation levels for cumulative emissions. Thus, it is useful to also give a more specific illustrative example. Figure 3.33 gives such an illustration by showing the importance of technological change assumptions in both reference and mitigation scenarios for a 550ppmv concentration target based on four SRES scenarios. Such analyses are increasingly becoming available. For instance, Placet et al. (2004) provide a detailed study of possible technology development pathways under climate stabilization for the US government Climate Change Technology Program. To illustrate the importance of technological change, actual projected scenario values in the original SRES no-climate policy sce-

\textsuperscript{22} 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.

\textsuperscript{23} In comparison, the full range of cumulative emissions from mitigation and stabilization scenarios in the database is from 214 to 1853 GtC.
narios are compared with a hypothetical case with frozen 1990 structures and technologies for both energy supply and end-use. The difference (denoted by a grey shaded area in Figure 3.33) illustrates the impact of technological change leading to improved efficiency and ‘decarbonization’ in energy systems, already incorporated into the baseline emission scenario.

**Figure 3.33:** Impact of technology on global carbon emissions in reference and climate mitigation scenarios.

*Note: Global carbon emissions (Gt CO₂) in four scenarios developed within the IPCC SRES and TAR (A2, B2 top and bottom of left panel; A1FI and A1B top and bottom of right panel). Grey shaded area indicated the difference in emissions between the original no-climate policy reference scenario compared with a hypothetical scenario assuming frozen 1990 energy efficiency and technology, illustrating the impact of technological change incorporated already into the reference scenario. Color shaded areas show the impact of various additional technology options deployed in imposing a 550 ppmv CO₂ stabilization constraint on the respective reference scenario including energy conservation (blue), substitution of high-carbon by low- or zero-carbon technologies (orange), as well as carbon capture and sequestration (black). Of particular interest are the two A1 scenarios shown on the right hand side of the panel that share identical (low) population and (high) economic growth assumptions making thus differences in technology assumptions more directly comparable.*

*Source: Adapted from Nakicenovic et al. (2000), IPCC (2001), Riahi and Roehrl (2001), and Edmonds (2004).*

The impacts of technological options leading to emission reductions is illustrated by colour shaded areas in Figure 3.33 regrouped into three categories: demand reductions (e.g. through deployment of more efficient end-use technologies such as lighting or vehicles), fuel switching (substitution of high GHG emitting technologies by low- or zero-emitting technologies such as renewables or nuclear), and finally, CO₂ capture and storage technologies. The mix in the mitigative technology portfolio required to reduce emissions from the reference scenario level to that consistent with the illustrative 550 ppmv stabilization target varies as a function of the baseline scenario underlying the model calculations (shown in Figure 3.33) as well as with the degree of stringency of the stabilization target adopted (not shown in Figure 3.33). An interesting finding from a large number of modelling studies is that scenarios with higher degrees of technology diversification (e.g. scenario A1B in Figure 3.33) also lead to a higher degree of flexibility with respect of meeting alternative climate (e.g. stabilization) targets and generally also to lower overall costs compared with less diversified technology scenarios. This illustrative example also confirms the conclusion reached in Section 3.3 that was based on a broader scenario literature.
This brief assessment of the role of technology across scenarios indicates that there is a significant
technological change and diffusion of new and advanced technologies already assumed in the base-
lines and additional technological change ‘induced’ through various policies and measures in the
mitigation scenarios. The newer literature on induced technological change assessed in the previous
sections along with other scenarios (e.g., Grubler, Nakicenovic and Nordhaus, 2002 and Köhler et
al., 2006, see also Ch. 11) also affirms this conclusion.

3.4.1 Carbon free energy and decarbonization

3.4.1.1 Decarbonization trends

Decarbonization denotes the declining average carbon intensity of primary energy over time (see
Kanoh, 1992). Although decarbonization of the world’s energy system is comparatively slow (0.3%
per year), the trend has persisted throughout the past 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. In short to medium term scenarios such a declining tendency for carbon
intensity may not be as discernable as across the longer term literature, e.g. in World Energy
Outlook 2004 (IEA, 2004), the reference scenario to 2030 shows the replacement of gas for other
fossil fuels as well as cleaner fuels due to limited growth of nuclear and bioenergy.

Another effect contributing toward reduction of carbon intensity of the economy is the declining
energy requirements per unit GDP, or energy intensity of GDP. Globally, energy intensity has been
decreasing more rapidly than carbon intensity of energy (0.9% per year) during the past two centuries
(Nakicenovic, 1996). Consequently, carbon intensity of GDP declined globally at about 1.2% per
year.

The carbon intensity of energy and energy intensities of GDP were shown in Section 3.2 of this
chapter, Figure 3.6, for the full scenario sample in the scenario database compared to the newer
(developed after 2001) non-intervention scenarios. As in Sections 3.2 and 3.3, the range of the
scenarios in the literature until 2001 is compared with recent projections from scenarios developed
after 2001 (Nakicenovic et al., 2005).

The majority of the scenarios in the literature portray a similar and persistent decarbonization trend
as observed in the past. In particular, the medians of the scenario sets indicate energy
decarbonization rates of about 0.9 (pre-2001 literature median) and 0.6 (post-2001 median) % per
year which is a significantly more rapid decrease compared to the historical rates of about 0.3% per
year. Decarbonization of GDP is also more rapid (about 2.5% per year for both pre and post-2001
literature medians) compared with the historical rates of about 1.2% per year. As expected, the
intervention and stabilization scenarios have significantly higher decarbonization rates and the post-
2001 scenarios include a few with significantly more rapid decarbonization of energy extending
even into the negative range. This means that toward the end of the century these more extreme
decarbonization scenarios foresee net carbon removal from the atmosphere, e.g. through carbon
capture and storage in conjunction with large shares of biomass energy. Such developments
represent a radical paradigm shift compared to the current and more near term energy systems,
implying significant and radical technological changes.

In contrast, the scenarios that are most intensive in the use of fossil fuels lead to practically no
reduction in carbon intensity of energy, while all scenarios portray decarbonization of GDP. For
example, the upper bound of the recent scenarios developed after 2001 depict slightly increasing
(about 0.3% per year) carbon intensities of energy (A2 reference scenario, Mori, 2003, see Figure 3.8 comparing carbon emissions across scenarios in the literature presented in Section 3.2). Most notably, a few scenarios developed before 2001 follow an opposite path compared to 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., 2006). In contrast, there are just a very few scenarios in the post 2100 literature that envisage increases in carbon intensity of energy.

The highest rates of decarbonization of energy (up to 2.5% per year for the recent scenarios) are from scenarios that include a complete transition in the energy system away from carbon intensive fossil fuels. Clearly, the majority of these scenarios are intervention scenarios, although some non-intervention scenarios show drastic reductions in CO$_2$ intensities due to reasons other than climate policies (e.g., the combination of sustainable development policies and technology push measures to promote renewable hydrogen systems). 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 of 1.1% per year over the course of the century, compared to just 0.3% for the non-intervention scenarios. Note, nevertheless, that the modest increase in carbon intensity of energy improvements in the intervention scenarios above the 75 percentile of the distribution of the recent scenarios. The vast majority of these scenarios represent sensitivity analysis; have climate policies for mitigation of non-CO$_2$ greenhouse gas 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 US$/tC (about 2.7 US$/tCO$_2$) 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.

### 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 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 is one of the major technological challenges addressed in mitigation and stabilization scenarios.

Figures 3.34 and 3.35 show the ranges of energy technology deployment across scenarios by 2030 and 2100 for baseline (non-intervention) and intervention (including stabilization) scenarios, respectively. The deployment of energy technologies in general and of new technologies in particular is significant indeed, even through the 2030 period, but especially by 2100. The deployment ranges should be compared with the current total global primary energy requirements of some 440 EJ in 2000. Coal, oil and gas reach median deployment levels ranging from some 150 to
250 EJ by 2030. The variation is significantly higher by 2100 but even medians reach levels of close to 600 EJ for coal in reference scenarios and thereby exceeding by a half the current deployment of all primary energy technologies in the world. Deployment of nuclear and biomass is comparatively lower in the range of about 50 to 100 EJ by 2030 and up to ten times as much by 2100. This all indicates that radical technological changes occur across the range of scenarios.

**Figure 3.34a:** Deployment of primary energy technologies across pre-2001 scenarios by 2030: Left “error” bars show baseline (non-intervention) scenarios and right ones intervention and stabilization scenarios. Shown the full ranges of the distributions (full vertical line with two extreme tic marks), the 25th and 75th percentiles (gray area) and the median (middle tic mark)

**Figure 3.34b:** Deployment of primary energy technologies across pre-2001 scenarios by 2100: Left “error” bars show baseline (non-intervention) scenarios and right ones intervention and stabilization scenarios. Shown the full ranges of the distributions (full vertical line with two extreme tic marks), the 25th and 75th percentiles (gray area) and the median (middle tic mark)
Figure 3.35: Deployment of primary energy technologies across post-2001 scenarios by 2100: Left "error" bars show baseline (non-intervention) scenarios and right ones intervention and stabilization scenarios. Shown the full ranges of the distributions (full vertical line with two extreme tic marks), the 25th and 75th percentiles (gray area) and the median (middle tic mark).

The deployment ranges are large for each of the technologies but do not differ much comparing the pre-2001 with post-2001 scenarios over both time periods, up to 2030 and 2100. Thus while technology deployments are large in the mean and variance, the patterns have changed little in the new compared with the older scenarios. What is significant in both sets of literature is the radically different structure and portfolio of technologies between baseline and stabilization scenarios. Mitigation generally means significantly less coal, somewhat less natural gas and consistently more nuclear and biomass. What cannot be seen from this comparison, due to the lack of data and information about the scenarios, is the extent to which carbon capture and storage is deployed in mitigation scenarios. However, it is very likely that most of the coal and much of the natural gas deployment across stabilization scenarios occurs in conjunction with carbon capture and storage.
The overall conclusion is that mitigation and stabilization in emissions scenarios have a significant inducement on diffusion rates of carbon saving and zero-carbon energy technologies.

3.4.2 RD&D and investment patterns

As mentioned in Ch. 2, the private sector is leading global research and development of technologies that are close to market deployment while public funding is essential for the longer term and basic research. R&D efforts in the energy area are especially important for GHG emissions reduction.

Accelerating the availability of advanced and new technologies will be central to greatly reducing CO₂ emissions from energy and other sources. Innovation in energy technology will be integral to meeting the objective of emission reduction. Investment and incentives 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.

Thus, sufficient investment will be required to ensure the best technologies are brought to market in a timely manner. These investments and the resulting deployment of new technologies provide an economic value. Model calculations enable economists to quantify the value of improved technologies as illustrated for two technologies in Figure 3.36.

![Figure 3.36: The value of improved technology.](image)

**Figure 3.36: The value of improved technology.**

Note: Modelling studies enable to calculate the economic value of technology improvements that increase particularly drastically with increasing stringency of stabilization targets (750, 650, 500, and 450 ppmv respectively) imposed on a reference scenario (modelling after the IS92a scenario in this particular modelling study). Detailed model representation of technological interdependencies and competition and substitution is needed for a comprehensive assessment of the economic value of technology improvements. Left panel: cost savings (billions of 1990 US$) compared to the reference scenario when lowering the costs of solar photovoltaic from a reference value of 9 US cents per kWh (top) by 1, 3, 4, and 6 cents/kWh respectively. For instance, the value of reducing PV costs from 9 to 3 cents per kWh could amount to up to 1.5 trillion dollars in an illustrative 550 ppmv stabilization scenario compared to the reference scenario in which costs remain at 9 cents/kWh. Right panel: cost savings resulting from availability of an ever larger and diversified portfolio of carbon capture and sequestration technologies. For instance, adding soil carbon sequestration to the portfolio of carbon capture and sequestration technology options (forest-sector measures were not included in the study) reduces costs by 1.1 trillion dollars in an illustrative 450 ppmv stabilization scenario. Removing all carbon capture and sequestration technologies would triple the costs of stabilization for all concentration levels analysed.

Source: GTSP
Generally, economic benefits from improved technology increase non-linearly with: a) the distance to current economic characteristics (or the ones assumed to be characteristic of the scenario baseline); b) the stringency of environmental targets; and c) the comprehensiveness and diversity of a particular technology portfolio considered in the analysis. Thus, the larger the distance between future technology characteristics compared to current ones, the lower the stabilization target, and the more comprehensive the suite of available technologies, the larger will be the economic value of improvements in technology.

These results lend further credence to technology R&D and deployment incentives policies (for example prices\textsuperscript{24}) as “hedging” strategies addressing climate change. However, given the current insufficient understanding of the complexity of driving forces underlying technological innovation and cost improvements, cost-benefit or economic “return on investment” calculations have to date not been attempted in the literature, due at least in part to a paucity of empirical technology-specific data on R&D and niche market deployment expenditures and the large uncertainties involved in linking “inputs” (R&D and market stimulation costs) to “outputs” (technology improvements and cost reductions).

3.4.3 Dynamic 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 on both technological innovation and implementation of technologies (a conclusion broadly confirmed in Ch. 2, Section 2.8.2.2). The rate of introduction of new technologies, and the drivers for adoption are however different across different parts of the world and in particular in industrial market economies, economies in transition and developing countries. This is to an extent reflected in global emissions scenarios as they often involve technological change at a level of a dozen or so world regions. This usually involves making more region specific assumptions about future performance, costs and investment needs for new and low carbon technologies.

There are multiple policy approaches to encourage technological innovation and change. Through regulation of energy markets, environmental regulations, energy efficiency standards, financial and other market-based incentives 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 and lower and upper bounds on technology diffusion.

3.4.3.2 Dynamics of technology

R&D, technological learning, and spillovers are the three broad categories of drivers of technological change. These are discussed in Ch. 2 Sections 2.8.2.2, and Ch. 11 Section 11.5. The main conclusion is that, on the whole, all three of the sources of induced technological change (ITC) play important roles in technological advance. Here, we focus on the dynamics of technology and ITC in emissions and stabilization scenarios.

Technological change is treated largely as an exogenous assumption about costs, market penetration and other technology characteristics in emissions scenarios with some notable exceptions such as in

\textsuperscript{24} See Newell et al., 1999.
Gritsevskyi and Nakicenovic (2000). Hourcade and Shukla (2001), in their review of scenarios from top-down models, indicate that technology assumptions play a critical factor affecting the timing and cost of emission abatement in the models. They identify widely differing costs of stabilization at 550 ppmv by 2050 of between 0.2 to 1.75% of GDP, mainly influenced by the size of the emissions in the baseline.

The International Modelling Comparison Project (IMCP) (Edenhofer et al., 2006) compared the treatment relating to technological change in many models covering a wide range of approaches. The economies for technological change were simulated in three groups: effects through R&D expenditures, learning-by-doing (LBD) or specialization and scale. IMCP finds that ITC reduces costs of stabilization, but in a wide range, depending on the flexibility of the investment decisions and the range of mitigation options in the models. It should be noted, however, that induced technological change is not a “free-lunch” as it requires higher upfront investment and deployment of new technologies in order to achieve cost-reductions thereafter. This can lead to lower overall mitigation costs.

All models indicate that real carbon prices for stabilization targets rise with time in the early years, with some models showing a decline in the optimal price after 2050 due to the accumulated effects of LBD and positive spillovers on economic growth. Another robust result is that ITC can reduce costs when models include low carbon energy sources, such as renewables and nuclear and carbon capture and sequestration, as well as energy efficiency and energy savings. Finally, policy uncertainty is seen as an issue. Long-term and credible abatement targets and policies will reduce some of the uncertainties around the investment decisions and are crucial to the transformation of the energy system.

ITC broadens the scope of technology related policies and usually increases the benefits of early action, which accelerates deployment and cost-reductions of low-carbon technologies (Barker et al., 2006; Sijm, 2004; 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, though this too may result in reduced cost of emission reduction (European Commission, 2003).

Other recent work also confirms these findings. 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. Nakicenovic and Riahi (2003) noted how the assumption about the availability of future technologies was a strong driver of stabilization costs. Edmonds et al. (2004-a) studied stabilization at 550 ppmv CO₂ 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. Weyant (2004) concluded that stabilization 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, models investigating induced technical change emerged during the mid and late 1990s. These models show that ITC can alter results in many ways. 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 the 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 decarbonized 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 confirmed in IMCP (Edenhofer et al., 2006). These results suggest that it is not possible to choose an ‘optimal’ direction of energy system development. Some modelling reported in TAR suggests that up to a 5 GtC a year reduction by 2020 (some 50% 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 100 US$/tC-equivalent (27 US$/tCO$_2$-eq.).

3.4.3.3 Barriers to technology transfer, diffusion and deployment for long-term mitigation

A discussion of barriers to development and commercialization of technologies is carried out in Ch. 2, section 2.9.2.3. Barriers to technology transfer vary according to the specific context from sector to sector and can manifest themselves differently in developed and developing countries, and in economies-in-transition (EITs). These barriers range from a 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.

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 short-term national policies would be driven by environmental concerns. National policies driven by energy security concerns can, however, have strong alignment with climate goals. The success of policies that address short-term development concerns will determine the pace at which convergence of the quality of life in the developing and the developed world occurs over the long-term.

In the long term, the key drivers of technological change in developing countries will depend on three ‘changes’ that are simultaneous and inseparable within the context of development: exogenous behavioral changes or changes in social infrastructure; endogenous policies driven by ‘development goals’; and any induced change from climate policies. (Shukla et al., 2006).
3.5 Interaction between mitigation and adaptation, in the light of climate change impacts and decision making under long run uncertainty

3.5.1 The interaction between mitigation and adaptation an iterative climate policy process

Responses to climate change include a portfolio of measures: a) mitigation - actions that reduce net carbon emissions and limit long-term climate change; b) adaptation - actions that help human and natural systems to adjust to climate change; c) research on new technologies, on institutional designs and on climate and impacts science, which should reduce uncertainties and facilitate future decisions (Richels et al. 2004; Caldeira et al. 2003; Yohe et al. 2004). A key question for policy is what combination of near- and long-term actions will minimize total costs of climate change, in whatever form these costs are expressed, across mitigation, adaptation and the residual climate impacts that society is either prepared or forced to tolerate. Although there are different views on the form and dynamics of such trade-offs in climate policies, there is a consensus that they should be aligned with (sustainable) development policies since the latter determine both the capacity to mitigate and to adapt in the future (TAR, Hourcade et al., 2001). In all cases, policy decisions will have to be made with incomplete understanding of the magnitude and timing of climate change, of its likely consequences, and of the cost and effectiveness of response measures.

3.5.1.1 An iterative risk management framework to articulate options

Previous IPCC reports conclude that climate change decision-making is not a once-and-for-all event, but an iterative risk management process that is likely to take place over decades where there will be opportunities for learning and mid-course corrections in light of new information (Smith et al. 2001, Lempert et al. 2004, Keller et al. 2006). This iterative process can be described using a decision tree (Figure 3.37) where the square nodes represent decisions, the circles represent the reduction of uncertainty and the arrows indicate the range of decisions and outcomes. Some nodes summarize today’s options - how much should be invested in mitigation, in adaptation, in expanding mitigative and adaptive capacity, or in research to reduce uncertainty? Other nodes represent opportunities to learn and make mid-course corrections. This picture is a caricature of real decision processes, which is continuous, overlapping and iterative. It is useful however to conceptually put the many determinants of any near-term strategy in a context of progressive resolution of uncertainty.
3.5.1.2  Qualitative insights on interactions between mitigation, adaptation and development

Until recently, a main focus in the policy and integrated assessment literature has been on comparing mitigation costs and avoided damages. Since the TAR, attention has shifted towards the interaction between mitigation and adaptation in reducing damages in a risk management framework. This has accompanied a growing realization that some climate change in the coming decades is inevitable.

Limited treatment of adaptation in climate policy assessments is still a problem and a number of reasons explain this. First, the focus of the international climate change negotiations has largely been on mitigation (perhaps because attention to adaptation could be viewed as ‘giving up’ on mitigation) even though the importance of adaptation is underlined in Article 4 of the UNFCCC and Article 10 of the Kyoto Protocol. Second, adaptation is largely undertaken at the local scale, by individual households, farmers, companies or local governments; it is thus difficult to target through coordinated international incentives and is more complicated to handle quantitatively by models in global scenarios. Third, it is difficult to generalize the ways that individuals or communities are likely to adapt to specific impacts. The literature however is evolving quickly and recent work is available in a number of regions. For example, in Finland (Carter et al. 2005), in the United Kingdom (West and Gawith 2005), in Canada (Cohen et al. 2004) and in the United States (e.g. California, Hayhoe et al. 2004).

Despite the scarcity of global systematic assessments (Tol, 2005a), some interesting insights on the interaction between adaptation and mitigation emerge from recent studies on a regional-scale. Some adaptation measures are ‘no-regret’ and should be undertaken anyway (Agrawala et al. 2005), such as preservation of mangroves in coastal zones, which provide a buffer for increased coastal flood risk due to climate change and help to maintain healthy marine ecosystems. A few may be synergistic with mitigation (Bosello 2005; Nicholls et al. 2006) such as investment in more efficient buildings that will limit human vulnerability to increasingly frequent heat waves and also reduce energy use, hence emissions. But many adaptation options involve net costs with a risk of committing to irreversible and misplaced investment given the large uncertainty about climate change at a local scale. Given this uncertainty, and the fact that learning about adaptation to climate change imposes some costs and takes time (Kelly et al. 2005), mis-allocation of investments may occur, or the rate

Finally, the interactions between adaptation and mitigation are intertwined with development pathways. A key issue is to understand at what point, (over)investment in mitigation or adaptation might limit funds available for development, and thus reduce future adaptive capacity (Sachs 2004, Tol 2005a, Tol and Yohe 2006). Another issue is at what point climate change damages, and the associated investment in adaptation, could crowd out more productive investments later and harm development (Kemfert 2002; Bosello and Zhang 2005; Kemfert and Schumacher 2005). The answer to these questions depends upon modelling assumptions that drive repercussions in other sectors of the economy and other regions and the potential impacts on economic growth. These are “higher-order” social costs of climate change from a series of climate change-induced shocks; they include the relative influence of: a) the cross-sectoral interactions across all major sectors and regions; b) a crowding-out effect that slows down capital accumulation and technical progress especially if technical change is endogenous. These indirect impacts reduce development and adaptive capacity and may be of the same order of magnitude, or greater than, the direct impact of climate change (Fankhauser and Tol 2005; Roson and Tol 2006; Kemfert 2006).

Both the magnitude and the sign of the indirect macro-economic impacts of climate change are conditional upon the growth dynamics of the countries concerned. When confronted by the same mitigation policies and the same climate change impacts, economies experiencing strong disequilibrium (including “poverty traps”) and large market and institutional imperfections will not react in the same way as countries that are on a steady and high economic growth pathway. The latter are near what economists call their production frontier (the maximum of production attainable at a given point in time); the former are more vulnerable to any climatic shock or badly calibrated mitigation policies but symmetrically offer more opportunities for synergies between mitigation, adaptation and development policies. On the adaptation side for example, Tol and Dowlatbadi (2001) demonstrate that there is significant potential to reduce vulnerability to the spread of malaria in Africa. In some circumstances, mitigation measures can be aligned with development policies and alleviate important sources of vulnerability in these countries, such as dependency on oil imports or local pollution. But this involves transition costs over the coming ten to twenty years (higher domestic energy prices, higher investments in the energy sector), which in turn suggests opportunities for international cooperative mechanisms to minimize these costs.

Bosello (2005) shows complementarity between adaptation, mitigation and investment in R&D, whilst others consider these as substitutes (Tol 2005a). Schneider and Lane (2006) consider that mitigation and adaptation only trade off for small temperature increments where adaptation might be cheaper, whereas for larger temperature increases mitigation is always the cheaper option. Goklany (2003) promotes the view that a contribution of climate change to hunger, malaria, coastal flooding, and water stress (as measured by populations at risk) is small compared to that of non-climate-change-related factors, and that through the 2080s, efforts to reduce vulnerability would be more cost-effective in reducing these problems than would mitigation. This analysis neglects critical thresholds at the regional level (such as the temperature ceiling on feasibility of regional crop growth) and at the global level (such as the onset of ice sheet melting or release of methane from permafrost), and, like many others studies, it neglects the impacts of extreme weather events. It also promotes a very optimistic view of adaptive capacity, which is increasingly challenged in the literature (Luers and Moser, 2005; Tompkins and Adger 2005). An adaptation-only policy scenario in the coming decades leads to an even greater challenge for adaptation in decades to follow, owing to the inertia of the climate system. In the absence of mitigation, temperature rises will be much greater than would otherwise occur with pursuant impacts on economic development (WGII, Ch.
19.3.7; Stern 2006). Hence adaptation alone is insufficient to avoid the serious risks due to climate change (see Table 3.11; also WGII, Ch. 19, Table 19.1).

In summary, adaptation and mitigation are thus viewed increasingly as complementary on the global scale, whilst locally there are examples of both synergies and conflicts between the two (WGII, Ch. 18). Less action on mitigation raises the risk of greater climate change induced damages to economic development and natural systems and implies a greater need for adaptation. Some authors hold that adaptation and mitigation are substitutes because of competition for funds, whilst others hold that such tradeoffs occur only at the margin when considering incremental temperature change and incremental policy action, because for large temperature changes mitigation is always cheaper than adaptation.

### 3.5.2 Linking emission scenarios to changes in global mean temperature, impacts and key vulnerabilities

In a risk management framework, a first step to understanding the environmental consequences of mitigation strategies is to look at linkages between various stabilisation levels for concentrations of greenhouse gases in the atmosphere, and the global mean temperature change relative to a particular baseline. A second step is to link levels of temperature change and key vulnerabilities. Climate models indicate significant uncertainty at both levels. Figure 3.38 shows CO$_2$ equivalent concentrations that would limit warming at equilibrium below the temperatures indicated above pre-industrial levels, for “best estimate” climate sensitivity, and for the likely range of climate sensitivity (see WG1, section 10.7, and Table 10.8; and the notes to Figure 3.38). It also shows the corresponding radiative forcing levels and their relationship to equilibrium temperature and CO$_2$-equivalent concentrations. The table and the figure illustrate how lower temperature constraints require lower stabilisation levels, and also that if the potential for climate sensitivities higher than the “best estimate” is taken into account, the constraint becomes more stringent. Such more stringent constraints lower the risks of exceedance of the threshold.

Figure 3.38 and table 3.10 provide an overview of how emission scenarios (section 3.3) relate to different stabilization targets and to the likelihood of staying below certain equilibrium warming levels. For example, respecting constraints of 2°C above pre-industrial, at equilibrium, is already outside the range of scenarios considered in this chapter if the higher values of likely climate sensitivity are taken into account (red curve in Figure 3.38), whilst a constraint of respecting 3°C above pre-industrial implies the most stringent of the A1 scenarios with emissions peaking in no more than the next 10 years, again if the higher likely values of climate sensitivity are taken into account. Using the best–estimate of climate sensitivity (i.e. the estimated mode) as a guide for establishing targets, implies the need for less stringent emission constraints. This ‘best estimate’ assumption shows that the most stringent (A1) scenarios could limit global mean temperature increases to 2.0–2.4°C above pre-industrial levels, at equilibrium, requiring emissions to peak within 10 years. Similarly, limiting temperature increases to 2°C above pre-industrial levels can only be reached at the lowest end of the concentration interval found in the A1 scenario category (i.e. about 450 ppmv CO$_2$-eq using ‘best estimate’ assumptions). By comparison, using the same ‘best estimate’ assumptions, category B scenarios could limit the increase to 2.8 – 3.2°C above pre-industrial levels at equilibrium, requiring emissions to peak within the next 25 years, whilst category C scenarios could limit the increase to 3.2 – 4.0°C above pre-industrial at equilibrium requiring emissions to peak within the next 55 years. Note that Table 3.10 category C scenarios could result in temperature increases as high as 6.1°C above pre-industrial when the likely range for the value of climate sensitivity is taken into account. Hence, setting policy on the basis of a “best estimate” climate sensitivity accepts a
significant risk of exceedance of the temperature thresholds, since the climate sensitivity could be higher than the best estimate.

Table 3.11 highlights a number of climate change impacts and key vulnerabilities organised as a function of global mean temperature rise (WGII Ch. 19). The table highlights a selection of key vulnerabilities representative of categories covered in WGII, Ch. 19 (Table 19.1). The italic text in Table 3.11 highlights examples of avoided impacts derived from ensuring that temperature is constrained to any particular temperature range compared to a higher one. For example, significant benefits result from constraining temperature change to not more than 1.6 - 2.6°C above pre-industrial levels. The benefits would include lowering (with different levels of confidence) the risk of: widespread deglaciation of the Greenland Ice Sheet; avoiding large-scale transformation of ecosystems and degradation of coral reefs; preventing terrestrial vegetation’s becoming a carbon source; constraining species extinction to between 10-40 per cent; preserving many unique habitats (see WGII, Ch. 4, Table 4.1 and Figure 4.5) including much of the Arctic; reducing increases in flooding, drought, and fire; reducing water quality declines, and preventing global net declines in food production. Other benefits of this constraint, not shown in the table 3.11, include reducing the risks of extreme weather events, and of at least partial deglaciation of the West Antarctic Ice Sheet (WAIS)* (WGII, Section 19.3.7). By comparison, for best guess climate sensitivity, attaining these benefits becomes unlikely if emissions reductions are postponed beyond the next 15 years to a time period between the next 15-55 years. Such postponement also results in increasing risks of a breakdown of the Meridional Overturning Circulation (WGII, Table 19.1).

Even for a 2.6-3.6°C temperature rise above pre-industrial there is also medium confidence in net negative impacts in many developed countries (WGII, Section 19.3.7). For emissions reduction scenarios resulting in likely temperature increases in excess of 3.6°C above pre-industrial, successively more severe impacts result. Low temperature constraints are necessary to avoid significant increases in the impacts in less developed regions of the world and in polar regions, since many market sectors in developing countries are already affected below 2.6°C above pre-industrial (WGII, Section 19.3.7), and indigenous populations in high latitude areas already face significant adverse impacts.

Table 3.9. Global mean temperature increase at equilibrium, greenhouse gas concentration and radiative forcing. Equilibrium temperatures here are calculated using estimates of climate sensitivity and do not take into account the full range of bio-geophysical feedbacks that may occur.

<table>
<thead>
<tr>
<th>Equilibrium temperature increase in °C above pre-industrial</th>
<th>CO₂ equivalent concentration and radiative forcing corresponding to best estimate of climate sensitivity for warming level in column 1 (1) (2)</th>
<th>CO₂ equivalent concentration that would be expected to limit warming below level in column 1 with an estimated likelihood of about 80% (13)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>319</td>
<td>0.7</td>
</tr>
<tr>
<td>1.6</td>
<td>402</td>
<td>2.0</td>
</tr>
<tr>
<td>2.0</td>
<td>441</td>
<td>2.5</td>
</tr>
<tr>
<td>2.6</td>
<td>507</td>
<td>3.2</td>
</tr>
<tr>
<td>3.0</td>
<td>556</td>
<td>3.7</td>
</tr>
<tr>
<td>3.6</td>
<td>639</td>
<td>4.5</td>
</tr>
<tr>
<td>4.0</td>
<td>701</td>
<td>4.9</td>
</tr>
<tr>
<td>4.6</td>
<td>805</td>
<td>5.7</td>
</tr>
<tr>
<td>5.0</td>
<td>883</td>
<td>6.2</td>
</tr>
<tr>
<td>5.6</td>
<td>1014</td>
<td>6.9</td>
</tr>
<tr>
<td>6.0</td>
<td>1112</td>
<td>7.4</td>
</tr>
<tr>
<td>6.6</td>
<td>1277</td>
<td>8.2</td>
</tr>
</tbody>
</table>
Notes:
1. WGI finds that the climate sensitivity is likely to be in the range 2 to 4.5°C, with a best estimate of about 3°C, very unlikely to be less than 1.5°C and values substantially higher than 4.5°C cannot be excluded. [WGI SPM]
2. The simple relationships $T_{eq} = T_{2\times CO_2} \times \ln([CO_2]/278)/\ln(2)$ and $\Delta Q = 5.35 \times \ln([CO_2]/278)$ are used. Nonlinearities in the feedbacks (including e.g., ice cover and carbon cycle) may cause time dependence of the effective climate sensitivity, as well as leading to larger uncertainties for greater warming levels. This likelihood level is consistent with the WGI assessment of climate sensitivity, see Note 1, and drawn from additional consideration of Box 10.2, Figure 2, in the WG I AR4.

![Equilibrium global mean temperature increase above preindustrial (°C)](image)

**Figure 3.38:** Relationship between Global Mean Temperature change and stabilisation concentration of greenhouse gases using (i) “best estimate” climate sensitivity of 3°C (black), (ii) upper bound of likely range of climate sensitivity of 4.5°C (red) (iii) lower bound of likely range of climate sensitivity of 2°C (blue).

Notes:
1. WGI finds that the climate sensitivity is likely to be in the range 2 to 4.5°C, with a best estimate of about 3°C, very unlikely to be less than 1.5°C and values substantially higher than 4.5°C cannot be excluded. [WGI SPM]
2. The simple relationship $T_{eq} = T_{2\times CO_2} \times \ln([CO_2]/280)/\ln(2)$ is used (see WGI, 10.7, and Table 10.8), with upper and lower values of $T_{2\times CO_2}$.
3. Nonlinearities in the feedbacks (including e.g., ice cover and carbon cycle) may cause time dependence of the effective climate sensitivity, as well as leading to larger uncertainties for greater warming levels. This likelihood level is consistent with the WGI assessment of climate sensitivity, see Note 1, and drawn from additional consideration of Box 10.2, Figure 2, in the WG I AR4.

It is possible to use stabilisation metrics (i.e. global mean temperature increase, concentrations in ppmv CO$_2$-eq or radiative forcing in W/m$^2$) in combination with the mitigation scenarios literature to assess the cost of alternative mitigation pathways that respect a given equilibrium temperature, key vulnerability (KV) or impact threshold. Whatever the target, both early and delayed-action mitigation pathways are possible, including ‘overshoot’ pathways that temporarily exceed this level. A delayed mitigation response leads to lower discounted costs of mitigation but accelerates the rate of change and the risk of transiently overshooting pre-determined targets (WGII, Section 19.4.2).

A strict comparison between mitigation scenarios and KVs is not feasible as KVs in Table 3.11 refer to realized transient temperatures in the 21st century rather than equilibrium temperatures, but a less rigorous comparison is still insightful. Avoidance of many KVs requires temperature change in 2100 to be below 2°C above 1990 levels (or 2.6°C above pre-industrial levels). Using equilibrium temperature as a guide, impacts or KV could be less than expected, for example if impacts do not occur until the 22nd century because there is more time for adaptation. Or they might be greater than...
expected as temperatures in the 21st century may transiently overshoot the equilibrium, or stocks at
risk such as human populations might be larger. Some studies explore the link between transient and
equilibrium temperature change for alternative emission pathways (O’Neill and Oppenheimer,
2004; Schneider and Mastrandrea, 2005; Meinshausen, 2006).

It is transient climate change, rather than equilibrium change, that will drive impacts. More research
is required to address the question of emission pathways and transient climate changes and their
links to impacts. In the meantime, equilibrium temperature change may be interpreted as a gross
indicator of change, and given the caveats above, as a rough guide for policymakers’ consideration
of KV and mitigation options to avoid KV.

25 see WGII 19.4, Figure 19.2; WGI,10.7 for further discussion of equilibrium and transient temperature increases in
relation to stabilisation pathways
Table 3.10: Properties of emissions pathways for alternative ranges of CO₂ and CO₂-eq. stabilization targets. Post-TAR stabilization scenarios in the scenario database (see also sections 3.2 and 3.3; data source: after Nakicenovic et al., 2006 and Hanaoka et al., 2006)

<table>
<thead>
<tr>
<th>Class</th>
<th>Anthropogenic addition to radiative forcing at stabilization (W/m²)</th>
<th>Multigas concentration level (ppmv CO₂-eq)</th>
<th>Stabilisation level for CO₂ only, consistent with multigas level (ppmv CO₂)</th>
<th>Number of scenario studies</th>
<th>Global mean temperature ºC increase above pre-industrial at equilibrium, using best estimate of climate sensitivity (3)</th>
<th>Likely range of global mean temperature ºC increase above pre-industrial at equilibrium (1)</th>
<th>Peaking year for CO₂ emissions (2)</th>
<th>Change in global emissions in 2050 (% of 2000 emissions) (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>2.5 - 3.0</td>
<td>440 - 490</td>
<td>350 - 400</td>
<td>6</td>
<td>2.0 - 2.4</td>
<td>1.4 - 3.6</td>
<td>2000 - 2015</td>
<td>-85 to -50</td>
</tr>
<tr>
<td>A2</td>
<td>3.0 - 3.5</td>
<td>490 - 535</td>
<td>400 - 440</td>
<td>18</td>
<td>2.4 - 2.8</td>
<td>1.6 - 4.2</td>
<td>2000 - 2020</td>
<td>-60 to -30</td>
</tr>
<tr>
<td>B</td>
<td>3.5 - 4.0</td>
<td>535 - 590</td>
<td>440 - 480</td>
<td>21</td>
<td>2.8 - 3.2</td>
<td>1.9 - 4.9</td>
<td>2010 - 2030</td>
<td>-30 to +5</td>
</tr>
<tr>
<td>C</td>
<td>4.0 - 5.0</td>
<td>590 - 710</td>
<td>480 - 570</td>
<td>118</td>
<td>3.2 - 4.0</td>
<td>2.2 - 6.1</td>
<td>2020 - 2060</td>
<td>+10 to +60</td>
</tr>
<tr>
<td>D</td>
<td>5.0 - 6.0</td>
<td>710 - 850</td>
<td>570 - 660</td>
<td>9</td>
<td>4.0 - 4.9</td>
<td>2.7 - 7.3</td>
<td>2050 - 2080</td>
<td>+25 to +85</td>
</tr>
<tr>
<td>E</td>
<td>6.0 - 7.5</td>
<td>850 - 1130</td>
<td>660 - 790</td>
<td>5</td>
<td>4.9 - 6.1</td>
<td>3.2 - 8.5</td>
<td>2060 - 2090</td>
<td>+90 to +14</td>
</tr>
</tbody>
</table>

Notes:
1. Warming for each stabilization class is calculated based on the variation of climate sensitivity between 2-4.5ºC, which corresponds to the likely range of climate sensitivity as defined by WGI (Ch 10).
2. Ranges correspond to the 70% percentile of the Post-TAR scenario distribution.
3. “Best estimate” refers to the most likely value of climate sensitivity, i.e. the mode (see WGI, chapter 10) and Table 3.9.
<table>
<thead>
<tr>
<th>GMT range relative to 1990 (pre-industrial)</th>
<th>Geophysical systems</th>
<th>Global biological systems</th>
<th>Global social systems</th>
<th>Regional systems</th>
<th>Extreme Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;4 (&lt;4.6)</td>
<td>Greenland ice sheet</td>
<td>Example: terrestrial ecosystems (WGII 4.4.11;1.3.4;1.3.5)</td>
<td>Example: water (WGII 3 ES; 3.4.3;13.4.3)</td>
<td>Example: Polar Regions (WGII 15.4.1;15.4.2;15.4.6;15.4.7)</td>
<td>Example: fire risk (WGI 7.3; WGII 1.3.6)</td>
</tr>
<tr>
<td>3-4 (3.6-4.6)</td>
<td>Near-total deglaciation**</td>
<td>Large-scale transformation of ecosystems and ecosystem services** At least 35% of species committed to extinction (3°C)</td>
<td>Severe droughts, droughts, erosion, water quality deterioration will increase with increasing climate change.**</td>
<td>Further declines in global food production of*</td>
<td>Frequency and intensity likely to be greater, especially in boreal forests and dry peat lands after melting of permafrost**</td>
</tr>
<tr>
<td>2-3 (2.6-3.6)</td>
<td>Commitment to widespread** to near-total deglaciation.*</td>
<td>Global vegetation becomes net source of C above 2-3°C <em>/</em>*</td>
<td>Sea level rise will extend areas of salinization of ground water, decreasing freshwater availability to coastal areas.***</td>
<td>Global food production peaks and begins to decrease of* (1-3°C)</td>
<td>While some economic opportunities will open up (e.g., shipping), traditional ways of life will be disrupted.**</td>
</tr>
<tr>
<td>1-2 (1.6-2.6)</td>
<td>Continued warming likely to lead to further loss of ice cover and permafrost**. Arctic ecosystems further threatened **, although net ecosystem productivity estimated to increase (o).</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-1 (0.6-1.6)</td>
<td>Increased fire frequency and intensity in many areas, particularly where drought increases**</td>
<td>Increased fire frequency and intensity in many areas, particularly where drought increases**</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**| Example: fire risk (WGI 7.3; WGII 1.3.6) | Example: fire risk (WGI 7.3; WGII 1.3.6) | Example: fire risk (WGI 7.3; WGII 1.3.6) | Example: fire risk (WGI 7.3; WGII 1.3.6) | Example: fire risk (WGI 7.3; WGII 1.3.6) | Example: fire risk (WGI 7.3; WGII 1.3.6) |

---

Table 3.11: Examples of key vulnerabilities (taken from WGII, Table 19.1)
Notes:
Plain text shows predicted vulnerabilities in various temperature ranges for global annual mean temperature rise relative to 1990. Italic text shows benefits (or damage avoided) upon constraining temperature increase to lower compared to higher temperature ranges.
Confidence symbol legend: o low confidence; * medium confidence; ** high confidence; *** very high confidence
Excerpts from II-Table 19.1:

a. Refer to Table 19.1 WGII for further information, also concerning Biogeochemical cycles, West Antarctic Ice Sheet and Meridional Overturning Circulation
b. Refer to Table 19.1 WGII for further information, also concerning marine and freshwater ecosystems
c. Refer to Table 19.1 WGII for further information, also concerning infrastructure, health, migration & conflict, and aggregate market impacts
d. Refer to Table 19.1 WGII for further information and also for other regions
e. Refer to Table 19.1 WGII for further information, also concerning tropical cyclones, flooding, extreme heat, and drought
3.5.3 Information for integrated assessment of response strategies

Based upon a better understanding of the links between concentration levels, magnitude and rate of warming and key vulnerabilities, the next step in integrated assessment is to inform decisions by combining information on climate science, impact analysis and economic analysis within a consistent analytical framework. These exercises can be grouped into three main categories depending on the way uncertainty is dealt with, the degree of complexity and multi-disciplinary nature of models and on the degree of ambition in terms of normative insights: i) assessment and sensitivity analysis of climate targets; ii) inverse analyses to determine emissions reductions corridors (trajectories) to avoid certain levels of climate change or of climate impacts iii) monetary assessment of climate change damages. How this information is used in economic analyses to determine optimal emissions pathways is discussed in 3.6.

3.5.3.1 Scenario and sensitivity analysis of climate targets

Probabilistic scenario analysis can be used to assess the risk of overshooting some climate target or to produce probabilistic projections that quantify the likelihood of a particular outcome. Targets for such analysis can be expressed in several different ways: absolute global mean temperature rise by 2100, rate of climate change, other thresholds beyond which dangerous anthropogenic interference (DAI) may occur, or additional number of people at risk to various stresses. For example, Arnell et al. (2002) show that such stresses (conversion of forests to grasslands, coastal flood risk, water stress) are far less at 550 ppm than at 750 ppm.

Recent IAM literature reflects a renewed attention to climate sensitivity, as a key driver of climate dynamics (den Elzen and Meinshausen, 2006; Hare and Meinshausen, 2006; Harvey, 2006; Keller et al., 2006; Mastrandrea and Schneider, 2004; Meehl et al., 2005; Meinshausen, 2005, 2006; O’Neil and Oppeinheimer, 2002, 2004; Schneider and Lane, 2004; Wigley, 2005). The consideration of a full range of possible climate sensitivity increases the probability of exceeding thresholds for specific DAI. It also magnifies the consequence of delaying mitigation efforts; Hare and Meinshausen (2006) estimate that each 10-year delay in mitigation implies an additional 0.2-0.3°C warming over a 100-400 year time horizon. For a climate sensitivity of 3°C, Harvey (2006) shows that immediate mitigation is required to constrain temperature rise to roughly 2°C above pre-industrial levels. Only in the unlikely situation where climate sensitivity is 1°C or lower would immediate mitigation not be necessary. Harvey also points out that, even in the case of 2°C threshold (above pre-industrial levels), acidification of the ocean would still occur and that this might not be considered safe.

Another focus of sensitivity analysis is on mitigation scenarios that overshoot and eventually return to a given stabilisation or temperature target (Khesghi, 2004; Wigley, 2005; Harvey, 2004; Izrael and Semenov, 2005; Khesghi et al., 2005; Meinshausen et al., 2005). Schneider and Mastrandrea (2005) find that this risk of exceedence of a threshold of 2°C above pre-industrial levels is increased by 70% for an overshoot scenario stabilizing at 500 ppm CO₂-equivalent (as compared to a scenario stabilizing at 500 ppm CO₂-equivalent). Such overshoot scenarios are likely to be necessary if there is a decision to achieve stabilization of GHG concentrations close to or at current day levels. They are indeed likely to lower the costs of mitigation but, in turn, raise the risk of exceeding such thresholds (Keller et al. 2006, Schneider and Lane, 2004) and may limit the ability to adapt by increasing the rate of climate change, at least temporarily (Hare and Meinshausen 2005) O’Neill and Oppenheimer (2004) find that the transient temperature up to 2100 is as much, or more, controlled by the pathway to stabilization than by the stabilization target, and that overshooting can lead to a peak temperature increase that is higher than in the long-term (equilibrium) warming.

26 This is below the range accepted by WGI.
The last and important contribution of this approach is to test the sensitivity of results to carbon cycle and climate change feedbacks (Cox et al. 2000, Friedlingstein et al. 2001, Matthews 2005) and other factors that may affect carbon cycle dynamics, eg deforestation (Gitz and Ciais 2003). For example, carbon cycle feedbacks amplify warming (WG1, Ch. 10) and are omitted from most other studies that thus underestimate the risks of exceeding (or overshooting) temperature targets for a given effort of mitigation in the energy sector only. This could increase warming by up to 1 degree in 2100, according to a simple model (WG1, Ch 10). The amplification, together with further potential amplification due to feedbacks of uncertain magnitude such as the potential release of methane from permafrost, peat bogs and seafloor clathrates (WG1, Ch 10) are also not included in the analysis presented in Figure 3.38 and Table 3.10. This analysis reflects only known feedbacks for which the magnitude can be estimated and are included in GCMs. Hence, scenario and sensitivity analysis shows that the risks of exceedance of a given temperature threshold for a given temperature target may be higher than shown in Table 3.10 and Figure 3.38.

3.5.3.2 Inverse modelling and guardrail analysis

Inverse modelling approaches such as Safe Landing Analysis (Swart et al., 1998) and Tolerable Windows Approach (Toth, 2003), aim to define a guardrail of allowable emissions for sets of unacceptable impacts or intolerable mitigation costs. They explore how the set of viable emissions pathways is constrained by parameters such as the starting date, the rate of emission reductions, or the environmental constraints. They provide insights into the influence of short-term decisions for long-term targets by delineating allowable emissions corridor, but they do not prescribe unique emissions pathways as do cost-effectiveness or costs-benefit analysis.

For example, Toth et al. (2002) draw on climate impact response functions (CIRFs) by Fuessel et al. (2001) who use detailed bio-physical models to estimate regionally specific, non-monetized impacts for different sectors (i.e. agricultural production, forestry, water runoff and biome changes). They show that business-as-usual scenario of GHG emissions (which resembles the SRES A2 scenario) to 2040 precludes the possibility of limiting the worldwide transformation of ecosystems to 30 per cent or less, even under very high willingness to pay for the mitigation of GHG emissions afterwards. Some applications of guardrail analyses assess the relationship between emission pathways and abrupt change such as THC collapse (Bruckner and Zickfeld 2005, Rahmstorf and Zickfeld 2005). The latter study concludes that stringent mitigation policy reduces the probability of THC collapse but cannot entirely avoid the risk of shutdown.

Corfee-Morlot and Höhne (2003) conclude that only low stabilization targets (e.g. 450ppm CO$_2$ or 550 ppm CO$_2$ equivalent) significantly reduce the likelihood of climate change impacts. They use an inverse analysis to conclude that more than half of the SRES (baseline) emission scenarios leave this objective virtually out of reach as of 2020.

More generally, referring to table 3.10, if the peaking of global emissions is postponed beyond the next 15 years to a time period between the next 15-55 years, then constraining global temperature rise to below 2.0°C above 1990 (2.6°C above pre-industrial) becomes unlikely (using ‘best estimate’ assumptions of climate sensitivity), resulting in increased risks of occurrence of the impacts listed in Table 3.12 and discussed in section 3.5.2.
3.5.3.3 Cost-benefit analysis, damage cost estimates and social cost of carbon

The above analysis provides a means to eliminate those emissions scenarios that are outside sets of pre-determined guardrails for climate protection and provides the raw material for cost-effectiveness analysis of optimal pathways for GHG emissions. If one wants to determine these pathways through a cost-benefit analysis it is necessary to assess the trade-off between mitigation, adaptation and damages, and, consequently, to measure damages in the same monetary metric as mitigation and adaptation expenditures. Such assessment can be carried out directly in the form of willingness to pay for avoiding certain physical consequences.

Some argue that it is necessary to specify more precisely why certain impacts are undesirable and to comprehensively itemize the economic consequences of climate change in monetary terms. The credibility of such efforts has often been questioned, given a) uncertainty surrounding climate impacts and the efficacy of societal responses to them b) the controversial meaning of a monetary metric across different regions and generations (Jacoby, 2004). This explains why few economists have taken the step of monetising global climate impacts. At the time of the TAR, only three such comprehensive studies had been published (Mendelsohn et al. (2000), Nordhaus and Boyer (2000) and Tol (2002a,b). Their estimates ranged from negligible to 1.5 per cent of the GDP for global mean temperature rise of +2.5°C and Nordhaus and Boyer carefully warned: ‘Along the economically efficient emission path, the long-run global average temperature after 500 years is projected to increase 6.2 °C over the 1900 global climate. While we have only the foggiest idea of what this would imply in terms of ecological, economic, and social outcomes, it would make the most thoughtful people, even economists, nervous to induce such a large environmental change. Given the potential for unintended and potentially disastrous consequences…’

Progress has been made since the TAR in assessing the impacts of climate change. Nonetheless, as noted in Watkiss et al.(2005), estimates of the social cost of carbon (SCC) in the recent literature still reflect an incomplete sub-set of relevant impacts; many significant impacts have not yet been monetized (see also WGII; on SCC see WGII, Section 20.6) and others are calibrated in numeraires that may defy monetization for some time to come. Reviews exist of available estimates of SCC show that they span several orders of magnitude – ranges that reflect uncertainties in climate sensitivity, response lags, discount rates, the treatment of equity, the valuation of economic and non-economic impacts, and the treatment of possible catastrophic losses (WGII Ch. 20). The majority of available estimates in the literature also capture only impacts driven by lower levels of climate change (e.g. 3 °C above 1990 levels). Working Group II highlights available estimates of SCC that run from -3 to 95US$/tCO₂ from one survey but also note another survey has included a few estimates as high as 400US$/tCO₂ (WGII Ch. 20, ES and Section 20.6.1). However the lower bound of this range includes studies where climate change is presumed to be low and aggregate benefits accrue. Moreover, none of the aggregate estimates reflect the significant differences in impacts that will be felt across different regions; nor do they capture any of the social costs of other greenhouse gases. A more recent estimate by Stern (2006) is at the high end of these estimates at 85 US$/tCO₂ because an extremely low discount rate (of 0.1%) is used in calculating damages that include additional costs attributed to abrupt change and increases in global mean temperature for some scenarios in excess of 7°C (Nordhaus 2006b; Yohe 2006; Tol & Yohe 2006). The long-term high temperature scenarios are due to inclusion of feedback processes. Working Group II also highlights that social costs of carbon and other greenhouse gases could increase over time by 2 to 4% per year (WGII, Ch. 20 E.S. and Section 20.6.1)

For a given level of climate change, the discrepancies in estimates of social costs of carbon can be explained by a number of parameters highlighted in Figure 3.39. These stem from two different
types of questions: normative and empirical. Key normative parameters include the inter-temporal aggregation of damages through discount rates and aggregation methods for impacts across diverse populations within the same time period (Azar and Lindgren 2003, Howarth 2003; Ingham and Ulph 2004, Mastrandrea and Schneider, 2004) and are responsible for much of the variation.

**Figure 3.39: Factors influencing the social cost of carbon**

*Source: Downing et al. (2005).*

The other parameters relate to the empirical validity of their assessment given the poor quality of data and the difficulty of predicting how society will react to climate impacts in a given sector, at a given scale in future decades. Pearce (2003) suggests that climate damages and SCC may be overestimated due to the omission of possible amenity benefits in warmer climates of high latitude regions (Maddison 2001a, b) and possible agricultural benefits. However, overall it is likely that current SCC estimates are understated due to the omission of significant impacts that have not yet been monetized (WGII, Ch. 19 and 20, Watkiss et al. 2005).

Key empirical parameters that increase the social value of damages include:
- **climate sensitivity and response lag** Equilibrium temperature rise for a doubling of CO₂, and the modelled response time of climate to such a change in forcing. Hope (2006) in his PAGE 2002 model found that as climate sensitivity was varied from 1.5 to 5°C identified a strong correlation with SCC.
- **coverage of abrupt or catastrophic changes** such as the crossing of the THC threshold (Keller et al. 2004; Link and Tol 2004; Keller et al. 2000 and 2004; Mastrandrea and Schneider (2001); Hall and Behl (2006)) or the release of methane from permafrost and the weakening of carbon sinks. The Stern review (2006) finds that such abrupt changes may more than double the market damages (e.g. from 2.1% to 5% of global GDP) if temperatures were to rise by 7.4°C in 2200.
- **inclusion and social value of non-market impacts**: what value will future generations place on impacts, such as the quality of landscape or biodiversity?
- **valuation methods for market impacts such as value of life**
• **adaptative capacity**: social costs will be magnified if climate change impacts fall on fragile economies.

• **predictive capacity**: studies finding efficient adaptation assume that actors decide under perfect foresight (after a learning process) (Mendelsohn and Williams 2004). Higher costs are found if one considers the volatility of climate signals and transaction costs. For agriculture Parry *et al.* (2004) shows the costs of a mismatch between expectations and real climate change (sunk costs, value of real estates and of capital stock).

• **geographic downscaling**: Nordhaus (2006) using a geographic-economic cross-sectional (1990) database concludes that this downscaling leads to increase damage costs from previous 0.7 estimates to 3.0 per cent of world output for a 3°C increase in global mean temperature.

• **the propagation** of local economic and social shocks: this blurs the distinction between winners and losers. The magnitude of this type of indirect impact depends on the existence of compensation mechanisms, including direct assistance and insurance as well as on how the cross-sectoral interdependences and transition costs are captured by models (see 3.5.1).

The influence of this set of parameters, which are set differently in various studies, explain the wide range of estimates of the social cost of carbon.

In an economically-efficient mitigation response, the marginal costs of mitigation should be equated to the marginal benefits of emission reduction. The marginal benefits are the avoided damages for an additional tonne of carbon abated within a given emission pathway, also known as the social cost of carbon (SCC). As discussed in Section 3.6, both sides of this equation are uncertain, which is why a sequential or iterative decision-making framework, with progressive resolution of information, is needed. Despite a paucity of analytical results in this area, it is possible to draw on today's literature to make a first comparison between the range of SCC estimates and the range of marginal costs of mitigation across different scenarios. WGII, Ch 20 reviews ranges of SCC from available literature. Allowing for a range of SCC between 4 - 95 US$/tCO2 (14 - 350 US$/tC from Tol 2005b median and 95th percentile estimates) and assuming a 2.4% per year increase (WGII, Ch. 20), produces a range of SCC estimates for 2030 between 8-189 US$/tCO2. The mitigation studies in this chapter suggest carbon prices in 2030 of 1 to 24 US$/tCO2-equivalent for category C scenarios, 18-79 US$/tCO2-equivalent for category B scenarios and 31-121US$/tCO2-equivalent for category A scenarios (see sections 3.3 and 3.6).

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

In selecting the most appropriate portfolio of policies to deal with climate change, it is important to distinguish between the case of ‘certainty’, where the ultimate target is known from the outset, and a ‘probabilistic’ case, where there is uncertainty about the level of a ‘dangerous interference’ and about the costs of greenhouse gas abatement.

In the case of certainty, the choice of emissions pathway can be seen as a pure GHG budget problem depending on a host of parameters (discounting, technical change, socio-economic inertia, carbon cycle and climate dynamics, to name the most critical) that shape its allocation across time. IPCC SAR and TAR demonstrated why this approach is an oversimplification and therefore misleading. Policy-makers are not required to make once-and-for-all decisions binding their successors over very long time horizons and there will be ample opportunities for mid-course adjustments in light of new information. The choice of short-term abatement rate (and adaptation strategies) involves bal-
ancing the economic risks of rapid abatement now and the reshaping of the capital stock that could later be proven unnecessary, against the corresponding risks of delay. Delay may entail more drastic adaptation measures and more rapid emissions reductions later to avoid serious damages, thus necessitating premature retirement of future capital stock or taking the risk of loosing the option of reaching a certain target altogether (SAR, WGIII, SPM).

The calculation of such short-term “optimal” decisions in a cost-benefit framework assumes the existence of a metaphorical “benevolent planner” mandated by cooperative stakeholders. The planner maximizes total welfare under given economic, technical and climate conditions, given subjective visions of climate risks and attitudes towards risks. A risk-taking society might choose to delay action and take the (small) risk of triggering significant and possibly irreversible abrupt change impacts over the long-term. If society is risk averse - that is, interested in avoiding worst case outcomes – it would prefer hedging behaviour, implying more intense and earlier mitigation efforts.

A significant amount of material has been produced since the SAR and the TAR to upgrade our understanding of the parameters influencing the decisions about the appropriate timing of climate action in a hedging perspective. We review these recent developments, starting with insights from a body of literature drawing on analytical models or compact AIM. We then assess the findings from literature for near-term sectoral emission and mitigation estimates from top down economy wide models.

3.6.1 **Insights on the choice of a near term hedging strategy in the context of long-term uncertainty**

There are two main ways of framing the decision making approaches for addressing the climate change mitigation and adaption strategies. They depend on different metrics used to assess the benefits of climate policies: a) a cost effectiveness analysis that minimizes the discounted costs of meeting various climate constraints (concentration ceiling, temperature targets, rate of global warming), b) a cost-benefit analysis that employs monetary estimates of the damages caused by climate change and finds the optimal emissions pathway by minimizing the discounted present value of adaption and mitigation costs, co-benefits and residual damages.

The choice between indicators of the mitigation benefits reflects a judgment on the quality of the available information and its ability to serve as a common basis in the decision making process. Actually the necessary time to obtain comprehensive, non-controversial estimates of climate policy benefits imposes a trade-off between the measurement **accuracy** of indicators describing the benefits of climate policies (which diminishes as one moves down the causal chain from global warming to impacts and as one downscales simulation results) and their **relevance**, i.e. their capacity to translate information that policymakers may desire ideally prior to a fully-informed decision. Using a set of environmental constraints is simply a way of considering that, beyond such constraints, the threat of climate change might become unacceptable; in a monetary-metric, or valuation approach, the same expectation can be translated through using damage curves with **dangerous** thresholds. The only serious source of divergence between the two approaches is the discount rate. Within a cost-effectiveness framework environmental constraints are not influenced by discounting. Conversely, in a cost-benefit framework, some benefits occur later than costs and thus have a lower weighting when discounted.

3.6.1.1 **Influence of passing from concentration targets to temperature targets in a cost effectiveness framework**
New studies such as Den Elzen et al. (2006) confirm previous results. They establish that reaching a concentration target as low as 450ppm CO$_2$-eq, under even optimistic assumptions of full participation, poses significant challenges in 2030-2040 timeframe, with rapidly increasing emission reduction rates and rising costs. In a stochastic cost-effectiveness framework, reaching such targets requires a significant and early emissions reduction with respect to respective baselines.

But concentration ceilings are a poor surrogate for climate change risks: they bypass many links from atmospheric chemistry to ultimate damages and they only refer to long-term implications of global warming. A better proxy of climate change impacts can be found in global mean temperature: every regional assessment of climate change impacts refers to this parameter, making it easier for stakeholders to grasp the stakes of global warming for their region; one can also take into account the rate of climate change, a major determinant of impacts and damages.

Therefore, with a noticeable acceleration in the last few years, the scientific community has concentrated on the assessment of climate policies in the context of climate stabilisation around various temperature targets. These contributions have mainly examined the influence of the uncertainty about climate sensitivity on the allowable (short-term) GHGs emissions budget and on the corresponding stringency of the climatic constraints, either through sensitivity analyses (Böhringer et al., 2005; Caldeira et al., 2003; den Elzen and Meinshausen, 2006; Richels et al., 2004) or within an optimal control framework (Ambrosi et al., 2003; Yohe et al., 2004).

On the whole, these studies reach similar conclusions, outlining the significance of uncertainty about climate sensitivity. Ambrosi et al. (2003) demonstrates that the information value of climate sensitivity before 2030 given the significant economic regrets from a precautionary climate policy in the presence of uncertainty about this parameter. Such information might not be available soon (i.e. at least fifty years could be necessary - Kelly et al., 2000). Yohe et al. (2004) thus conclude: ‘uncertainty [about climate sensitivity] is the reason for acting in the near term and uncertainty cannot be used as a justification for doing nothing’.

A few authors analyze the trade-off between a costly acceleration of mitigation costs and a (temporary) overshoot of targets and the climate impacts of this overshoot. Ambrosi et al. (2003) did so through a willingness to pay for not interfering with the climate system. They show that allowing for overshoot of an 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 in the first period. However, the overshoot may significantly increase climate change damages as discussed above (see Section 3.5). Another result is that higher climate sensitivity magnifies the rate of warming, which in turn exacerbates adaptation difficulties, and leads to stringent abatement policy recommendations for the coming decades (Ambrosi, 2007). This result is robust to the choice of discount rate; uncertainty about the rate constraint is proven to be more important for short-term decisions than uncertainty about the magnitude of warming. Therefore, research should be aimed at better characterizing early climate change risks with a view to help decision makers in agreeing on a safe guardrail to limit the rate of global warming.

### 3.6.1.2 Implications of assumptions concerning damage functions in cost-benefit analysis

What is remarkable in cost-benefit studies of the optimal timing of mitigation is that the shape (or curvature) of the damage function matters even more than the ultimate level of damages – a fact long established by Peck and Teisberg (1995). With damage functions exhibiting smooth and regular damages (such as power functions with integer exponents or polynomial functions), GHG abatement is postponed. This is because, for several decades, the temporal rate of increase in mar-
ginal climate change damage remains low enough to conclude that investments to accelerate the rate of economic growth are more socially profitable than investing in abatement.

This result changes if singularities in the damage curve represent non-linear events. Including even small probabilities of catastrophic ‘nasty surprises’ may substantially alter optimal near-term carbon taxes (Mastrandea and Schneider 2004; Azar and Lindgren 2003). Many other authors report similar findings (Azar and Schneider (2001), Ingham and Ulph (2003) Howarth (2003), Dumas and Ha-Duong (2004), Baranzini et al. (2003)), whilst Hall and Behl (2006) suggest a damage function reflecting climate instability needs to include discontinuities in capital stock and rate of return on capital, and hysteresis with respect to heating and cooling – resulting in a non-convex optimization function such that economic optimization models can have no solution. But these surprises may be caused by forces other than large catastrophic events. They may also be triggered by smooth climate changes that exceed a vulnerability threshold (e.g. shocks to agricultural systems in developing countries leading to starvation) or by policies that lead to mal-adaptations to climate change.

In the case of an irreversible THC collapse, Keller et al. (2004) point out another seemingly paradoxical result: if a climate catastrophe seems very likely within a near-term time horizon, it might be economically sound to accept its consequences instead of investing in expensive mitigation to avoid the inevitable. This both shows that temporary overshoot of a pre-determined target may be preferable to bearing the social costs of an exaggerated reduction in emission; and the need to be attentive to “windows of opportunity” for abatement action. The converse argument is that timely abatement measures, especially in the case of ITC, can reduce long-term mitigation costs and avoid some of the catastrophic events. In this respect, limited differences in GMT curves for different emissions pathways within coming decades are often misinterpreted. It does not imply that early mitigation activities would make no material difference to long term warming. On the contrary, if the social value of damages is high enough to justify deep emission cuts decades from now, early action is necessary due to inertia in socio-economic systems. For example, one challenge is to avoid further build-up of carbon intensive capital stock.

### 3.6.2 Evaluation of short-term mitigation opportunities in long-term stabilization scenarios

#### 3.6.2.1 Studies reporting short-term sectoral reduction levels

While there are many potential emissions pathways to a particular stabilization target from a specific year, it is possible to define emissions trajectories based on near-term mitigation opportunities that are consistent with a given stabilization target. This section assesses scenario results by sector from top-down models for the year 2030 to evaluate the range of near-term mitigation opportunities in long-term stabilization scenarios. To put these identified mitigation opportunities in context, Chapter 11, Section 11.3.1.5 compares the near-term mitigation estimates across all of the economic sectors.

Many of the modelling scenarios represented in this section were an outcome from the Energy Modelling Forum Study 21 (EMF-21) which focused specifically on multi-gas strategies to address climate change stabilization (see de la Chesnaye and Weyant, 2006). Models that were evaluated in this assessment are listed in Table 3.12.

For each model, the resulting emissions in the mitigation case for each economic sector in 2030 were compared to projected emissions in a reference case. Results were compared across a range of stabilization targets. For more detail on the relationship between stabilization targets defined in concentrations, radiative forcing and temperature, please see Section 3.3.2.
Key assumptions and attributes vary across the models evaluated, impacting the results. Most of the top down models evaluated have a time horizon beyond 2050 such as AIM, IPAC, IMAGE, GRAPE, MiniCAM, MERGE, MESSAGE, and WIAGEM. Top down models with a time horizon up to 2050, such as POLES and SGM, were also evaluated. The models also vary in their solution concept. Some models solve based on intertemporal optimization, allowing mitigation options to be adopted with perfect foresight as to what the future carbon price will be. Other models solve based on a recursive dynamic, allowing mitigation options to be adopted based only on today’s carbon price. Recursive dynamic models tend to show higher carbon prices to achieve the same emission reductions as in intertemporal optimization models, because emitters do not have the foresight to take early mitigation actions which may have been cheaper (for more discussion on modeling approaches, refer to Section 3.3.3).

Three important considerations need to be remembered with regard to the reported carbon prices. First, these mitigation scenarios assume complete “what” and “where” flexibility, i.e., there is full substitution among GHGs and reductions take place anywhere in the world, according to the principle of least cost. Limiting the degree of flexibility in these mitigation scenarios, e.g., limiting mitigation only to CO$_2$, removing major countries or regions from undertaking mitigation, or both, will increase carbon prices, all else equal. Second, the carbon prices of realizing these levels of mitigation increase in the time horizon beyond 2030. See Figure 3.25 for an illustration of carbon prices across longer time horizons from top down scenarios. Third, at the economic sector level, estimated emission reduction for all greenhouse gases varies significantly across the different model scenarios, in part because each model uses sector definitions specific to that type of model.

Across all the models, the long-term target in the stabilization scenarios could be met through the mitigation of multiple greenhouse gases (CO$_2$, CH$_4$, N$_2$O and High GWP gases). However the specific mitigation options and the treatment of technological progress vary across the models. For example, only some of the models include carbon capture and storage as a mitigation option (GRAPE, IMAGE, IPAC, MiniCAM, and MESSAGE). In addition, some models include forest sinks as a mitigation option. The model results shown in Table 3.13 do not include forest sinks as a mitigation option, while the results shown in Table 3.14 do include forest sinks, as described in further detail below.

Table 3.13 illustrates the amount of global GHG mitigation reported by sector for the year 2030 across a range of multigas stabilization targets. Across the higher Category C stabilization target scenarios, emission reductions of 3 to 31% from the reference case emissions across all greenhouse gases can be achieved for a carbon price of 2 - 57 US$/tCO$_2$-eq. The results from the POLES models fall on the higher end of the price range, in part due to the recursive dynamic nature of the model, and also due to its shorter time horizon over which to plan. On the lower end of the price range are the results from the GRAPE model, which is the only intertemporally optimizing model shown in the higher stabilization scenarios. In the GRAPE results, only 3% of the emissions are reduced by 2030, implying that the majority of the mitigation necessary to meet the target is undertaken beyond 2030. In scenarios with lower Category A stabilization targets, higher levels of near-term mitigation are required to achieve the target in the long run, resulting in a higher range of prices. Emission reductions of approximately 35% can be achieved for a price of 9 - 92 US$/tCO$_2$-eq.

Several of the models included in the EMF-21 study also ran multigas scenarios that included forest sinks as a mitigation option. Table 3.14 shows the 2030 mitigation estimates for these scenarios that model net land use change including forest carbon sinks as a mitigation option. When terrestrial
sinks are modelled as a mitigation option, it can lessen the pressure to mitigate in other sectors. Further discussion of forest sequestration as a mitigation option is presented in section 3.3.5.5. Across the higher Category C stabilization target scenarios, emission reductions of 4 to 24% from the reference case emissions across all greenhouse gases can be achieved for a price of 2 - 21 US$/tCO$_2$-eq. In scenarios with lower Category A stabilization targets, emission reductions of 26 to 40% can be achieved for a price of 31 -121 US$/tCO$_2$-eq.
### Table 3.12: Top down models assessed for mitigation opportunities in 2030

<table>
<thead>
<tr>
<th>Model</th>
<th>Model Type</th>
<th>Solution Concept</th>
<th>Time Horizon</th>
<th>Modelling Team and Reference</th>
</tr>
</thead>
</table>

### Table 3.13: Global emission reductions from top-down models in 2030 by sector for multigas scenarios

<table>
<thead>
<tr>
<th>Model</th>
<th>POLES</th>
<th>IPAC</th>
<th>AIM</th>
<th>GRAPE</th>
<th>MiniCAM</th>
<th>SGM</th>
<th>MERGE</th>
<th>WIAGEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stabilization Category</td>
<td>Category C</td>
<td>Category A2</td>
<td>Category A1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stabilization Target</td>
<td>550 ppmv</td>
<td>550 ppmv</td>
<td>4.5 W/m² from pre-Industrial</td>
<td>4.5 W/m² from pre-Industrial</td>
<td>4.5 W/m² from pre-Industrial</td>
<td>From MiniCAM Trajectory</td>
<td>3.4 W/m² from pre-Industrial</td>
<td>2° C from pre-Industrial</td>
</tr>
<tr>
<td>Reference Emissions 2030 Total All Gases (GtCO₂-eq)</td>
<td>53.0</td>
<td>55.3</td>
<td>49.4</td>
<td>57.0</td>
<td>54.2</td>
<td>53.5</td>
<td>47.2</td>
<td>43.1</td>
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</table>

<table>
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<th></th>
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<th></th>
<th></th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>POLES</td>
<td>9.5</td>
<td>6.4</td>
<td>0.5</td>
<td>1.1</td>
<td>16</td>
<td>0.6</td>
<td>No mitigation options modelled</td>
<td></td>
</tr>
<tr>
<td>IPAC</td>
<td>0.5</td>
<td>0.6</td>
<td>0.5</td>
<td>0.4</td>
<td>1.7</td>
<td>0.6</td>
<td>No mitigation options modelled</td>
<td></td>
</tr>
<tr>
<td>AIM</td>
<td>0.5</td>
<td>0.6</td>
<td>0.5</td>
<td>0.4</td>
<td>1.7</td>
<td>0.6</td>
<td>No mitigation options modelled</td>
<td></td>
</tr>
<tr>
<td>GRAPE</td>
<td>0.8</td>
<td>0.0</td>
<td>0.8</td>
<td>0.3</td>
<td>1.7</td>
<td>1.7</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>MiniCAM</td>
<td>0.8</td>
<td>0.0</td>
<td>0.3</td>
<td>0.3</td>
<td>0.5</td>
<td>0.5</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>SGM</td>
<td>0.8</td>
<td>0.0</td>
<td>0.3</td>
<td>0.3</td>
<td>0.5</td>
<td>0.5</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>MERGE</td>
<td>0.8</td>
<td>0.0</td>
<td>0.3</td>
<td>0.3</td>
<td>0.5</td>
<td>0.5</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>WIAGEM</td>
<td>0.8</td>
<td>0.0</td>
<td>0.3</td>
<td>0.3</td>
<td>0.5</td>
<td>0.5</td>
<td>1.1</td>
<td></td>
</tr>
</tbody>
</table>

| Global Total | 16.4 | 8.7 | 10.6 | 1.9 | 11.9 | 11.2 | 16.3 | 15.5 |
| Mitigation as % Reference Emissions | 31% | 16% | 21% | 3% | 22% | 21% | 35% | 36% |

1. SGM sector mitigation estimates for Transportation Demand and Industry Production are not complete global representation due to varying levels of regional aggregation.
2. MERGE sector mitigation estimates for Industry Production, Agriculture, and Waste Management are aggregated. No Forestry mitigation options were modelled.
3. WIAGEM sector mitigation estimates do not sum to global total due to the breakout of the household and chemical sectors.
4. MiniCAM CO₂ mitigation from Industrial Production is accounted for in the Industry Demand.
5. Higher IPAC Agriculture emissions in the stabilization scenario than in the reference case reflects the loss of permanent forest due to growing bioenergy crops.
6. GRAPE Waste sector mitigation reflects only GDP activity factor changes in 2030, and reflects emission factor reductions in later years.
7. IPAC Waste sector cost-effective mitigation options are included in the baseline.
8. GRAPE CO₂ from cement production is included in Buildings Demand.
Table 3.14: Global emission reductions from top down models in 2030 by sector for multigas plus sinks scenarios

<table>
<thead>
<tr>
<th>Model</th>
<th>GRAPE</th>
<th>IMAGE 2.2</th>
<th>IMAGE 2.3</th>
<th>MESSAGE</th>
<th>MESSAGE</th>
<th>IMAGE 2.3</th>
<th>IMAGE 2.3</th>
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<td></td>
<td></td>
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<td></td>
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<tr>
<td>Stabilization Target</td>
<td>4.5 W/m² from pre-Industrial</td>
<td>4.5 W/m² from pre-Industrial</td>
<td>4.5 W/m² from pre-Industrial</td>
<td>B2 Scenario, 4.5 W/m² from pre-Industrial</td>
<td>A2 Scenario, 4.5 W/m² from pre-Industrial</td>
<td>3.7 W/m² from pre-Industrial</td>
<td>3.0 W/m² from pre-Industrial</td>
<td>B2 Scenario, 4.5 W/m² from pre-Industrial</td>
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<tr>
<td>Carbon price in 2030</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2000 US$/tCO₂-eq)</td>
<td>2</td>
<td>18</td>
<td>21</td>
<td>6</td>
<td>15</td>
<td>50</td>
<td>121</td>
<td>31</td>
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<tr>
<td>Reference Emissions 2030</td>
<td>57.0</td>
<td>65.5</td>
<td>59.7</td>
<td>57.8</td>
<td>70.9</td>
<td>59.7</td>
<td>59.7</td>
<td>57.8</td>
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<tr>
<td>Total All Gases (GtCO₂-eq)</td>
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<td></td>
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<tr>
<td>Electric</td>
<td>0.5</td>
<td>2.4</td>
<td>1.7</td>
<td>1.1</td>
<td>7.3</td>
<td>3.9</td>
<td>8.7</td>
<td>4.3</td>
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<td>Non-Electric</td>
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<td>1.6</td>
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<td>3.5</td>
<td>2.3</td>
<td>3.7</td>
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<tr>
<td>Transportation Demand</td>
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<td>0.7</td>
<td>0.3</td>
<td>1.0</td>
<td>1.5</td>
<td>2.8</td>
<td>2.2</td>
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<td>Buildings Demand</td>
<td>0.3</td>
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<td>0.3</td>
<td>0.5</td>
<td>1.2</td>
<td>0.5</td>
<td>1.0</td>
<td>1.4</td>
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<td>Industry Demand</td>
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<td></td>
<td></td>
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<tr>
<td>included in Buildings</td>
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<tr>
<td>Demand</td>
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<td>0.5</td>
<td>0.1</td>
<td>0.4</td>
<td>1.6</td>
<td>3.2</td>
<td>0.8</td>
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<tr>
<td>Industry Production</td>
<td>0.1²</td>
<td>1.1</td>
<td>0.8</td>
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<td>0.6</td>
<td>1.1</td>
<td>2.0</td>
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<td>Agriculture</td>
<td>0.3</td>
<td>0.7</td>
<td>0.6</td>
<td>0.6</td>
<td>1.5</td>
<td>1.0</td>
<td>1.2</td>
<td>1.7</td>
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<td>Forestry</td>
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<td>0.3</td>
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<td>0.2</td>
<td>0.2</td>
<td>0.6</td>
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<tr>
<td>Waste Management</td>
<td>0.0¹</td>
<td>0.7</td>
<td>1.0</td>
<td>0.9</td>
<td>1.1</td>
<td>1.0</td>
<td>1.1</td>
<td>0.9</td>
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<tr>
<td>Global Total</td>
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<td>11.5</td>
<td>7.6</td>
<td>4.4</td>
<td>16.8</td>
<td>13.0</td>
<td>24.0</td>
<td>15.0</td>
</tr>
<tr>
<td>Mitigation as % Reference</td>
<td>4%</td>
<td>18%</td>
<td>13%</td>
<td>8%</td>
<td>24%</td>
<td>22%</td>
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<td>26%</td>
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</tbody>
</table>

¹ GRAPE Waste sector mitigation reflects only GDP activity factor changes in 2030, and reflects emission factor reductions in later years.
² GRAPE CO₂ from cement production is included in Buildings Demand.
3.6.2.2 Assessment of reduction levels at different marginal prices

To put these identified mitigation opportunities in context, they will be compared with mitigation estimates from bottom up models. Chapters 4 through 10 describe mitigation technologies available in specific economic sectors. Chapter 11, Section 11.3.1.5 compares the near-term mitigation estimates across all of the economic sectors for selected marginal costs levels (20, 50 and 100 US$/tCO₂-equivalents). For that purpose, we have plotted the permit price and (sectoral) reduction levels of the different studies. These plots have been used to explore whether the combination of the studies suggests a certain likely reduction levels at the three target levels of 20, 50 and 100 US$/tCO₂-equivalents. As far more studies were available that reported economy-wide reduction levels than the ones that provided sectoral information, we were able to use a formal statistical method for the former. For the latter, a statistical method was also applied but outcomes have been used with more care.

Economy-wide reduction levels

Figure 3.30 shows the available data from studies that report economy-wide reduction levels (multigas) and permit prices. The data has been taken from the emission scenario database (Hanaoka et al., 2006; Nakicenovic et al., 2006) – and information directly reported in the context of EMF-21 (de la Chesnaye and Weyant, 2006) and IMCP (Ederhofer et al., 2006). The total sets suggests some form a relationship with studies reporting higher permit prices also, in general, reporting higher reduction levels.

Figure 3.40: Permit price versus level of emission reduction – total economy in 2030 (for the x-axis is the natural logarithm of the permit price is used). The uncertainty range indicated is the 68% interval.

Obviously, a considerable range in results is also found – which is function of factors such as 1) model uncertainties, including technology assumptions and inertia, 2) assumed baseline developments, and 3) the trajectory of the permit price prior to 2030.

The suggested relationship across the total is linear if permit prices are plotted on a logarithmic scale as shown in Figure 3.30. In other words, the relationship between the two variables is logarithmic, which is a form that is consistent with the general form of marginal abatement curves reported in literature: increasing reduction levels for higher prices but diminishing returns at higher
prices as the reduction tends to reach a theoretical maximum. The figure not only shows the best-guess regression line, but also 68% confidence interval. The latter can be used to derive the 68 percentile interval of the reduction potential for the 20 and 100 US$/tCO_2$-eq price levels, which are $13.3 \pm 4.6$ GtCO_2-eq/yr and $21.5 \pm 4.7$ GtCO_2-eq/yr, respectively.

**Sectoral estimates**

A more limited set of studies reported sectoral reduction levels. The same plot as Figure 3.30 has been made for the sectoral data (see Figure 3.31), again plotting the logarithm of the permit price against emission reduction levels. The data here is directly taken from Table 3.13 and Table 3.14. As fewer data are available, the statistical analysis becomes less strong. Nevertheless, for most sectors, a similarly formed relationship was found across the set of studies as for the economy-wide potential (logarithmic relationship showing an increasing reduction levels at relatively low prices, and a much slower increase at higher prices). As expected, in several sectors the spread across models in the 2030 set is larger than in the economy-wide estimates.

![Figure 3.41: Permit price versus emission reduction level – several sectors in 2030 (vertical lines indicate levels at 20, 50 and 100 US$/tCO_2$)](image)

In general, a relatively strong relationship is found in the sectors energy supply sector, transport, and industrial energy consumption. The relationship between the price and emission reduction level is less clear in other sectors – and more-or-less absent for the limited reported data on the forestry sector. It should be noted that here definitions across studies may be less well defined – and also, forest sector emissions may actually increase in mitigation scenarios as a result of net deforestation due to bio-energy production.
It should be noted that emission data (and thus also reduction levels) are reported on a ‘point of emission basis’ (emissions are reported for the sectors in which the emissions occur). For example, the efficiency improvements in end-use sectors for electricity lead to reductions in the energy supply sector. Likewise, application of bio-energy leads to emission reduction in the end-use sectors, but at the same time in some models may lead to increases in emissions in forestry due to associated land use changes. The latter may explain differences with the way data from top-down models is represented in elsewhere in this report as here in most cases only the emission changes from mitigation measures in the forestry sector itself are reported. It also explains why the potential is some of the end-use sectors is relatively small, as emission reductions from electricity savings are reported elsewhere.

**Reported estimates**

On the basis of the available data, the following ranges have been estimates for the reduction potential at a 20, 50 and 100 US$/tCO₂-eq price. As estimates have been made independently the total of the different sectors does not add up to the overall range (as expected the sum of the sectors gives a slightly wider range).

The largest potential is found in energy supply – covering both the electricity sector and energy supply – with a relatively high capability of responding to permit prices. Also relatively high reduction levels are found for the industry sector. Relatively small reduction levels are reported for the forestry sector and the waste management sector.

**Table 3.15: Reduction potential at various marginal prices, averages across different models (low and high indicate one standard deviation variation)**

<table>
<thead>
<tr>
<th></th>
<th>20 US$/tCO₂-eq</th>
<th>50 US$/tCO₂-eq</th>
<th>100 US$/tCO₂-eq</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Energy supply</td>
<td>3.9</td>
<td>9.7</td>
<td>6.7</td>
</tr>
<tr>
<td>Transport</td>
<td>0.1</td>
<td>1.6</td>
<td>0.5</td>
</tr>
<tr>
<td>Buildings</td>
<td>0.2</td>
<td>1.1</td>
<td>0.4</td>
</tr>
<tr>
<td>Industry</td>
<td>1.2</td>
<td>3.2</td>
<td>2.2</td>
</tr>
<tr>
<td>Agriculture</td>
<td>0.6</td>
<td>1.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Forestry</td>
<td>0.2</td>
<td>0.8</td>
<td>0.2</td>
</tr>
<tr>
<td>Waste</td>
<td>0.7</td>
<td>0.9</td>
<td>0.8</td>
</tr>
</tbody>
</table>

**Overall** ¹) 8.7 17.9 13.7 22.6 16.8 26.2

**Note: ¹) The overall potential has been estimated separately from the sectoral totals.**
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