Technology Dynamics and Greenhouse Gas Emissions Mitigation: A Cost Assessment

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ABSTRACT

This article analyzes long-term greenhouse gas (GHG) emissions and their mitigation in a family of high economic and energy demand growth scenarios in which technological change unfolds in alternative "path dependent" directions. Four variants of this family are developed and used as baseline scenarios, for which alternative policy cases leading to a stabilization of atmospheric CO_2 concentrations at 450, 550, 650, and 750 parts per million by volume (ppmv) by the end of the 21st century are examined. The baseline scenarios share common demographic, economic, and energy demand developments, but explore alternative development pathways of technological change and resource availability. We illustrate the sensitivity of projected future GHG emission levels and resulting global climate change to alternative developments in energy systems technologies. We conclude that uncertainties in technological change are as important for determining future GHG emissions as uncertainties in long-term demographic and economic developments. We also illustrate that differences in costs between alternative baseline scenarios of technological change may be larger than the cost differences of reaching alternative environmental (climate change stabilization) targets. Under our assumptions of high economic and energy demand growth, even in scenarios favoring fossil fuels, the long-term technology portfolio needs to include improvements in zero-carbon technologies and gas-related technologies and infrastructures. We suggest that improvements in these technology options are a robust hedging strategy for an uncertain energy future. © 2000 Elsevier Science Inc.

Introduction

The possibility of human-induced climate change raises a number of formidable analytical and policy challenges. Foremost among these challenges is the time scale of a century or more that is characteristic for interactions between human activities like energy production and use, resulting greenhouse gas (GHG) emissions, changes in the atmospheric concentrations of GHGs and their influence on changes in the radiative balance of the planet and, hence, climate change and its impacts. The nature of these interactions are highly uncertain. Yet, to understand the possible magnitude of the problem and likely consequences on society and nature, it is necessary to explore the very long term—a century, in the case of the calculations reported here. Uncertainties in long-term demographic and economic developments have been explored in numerous

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scenario studies of GHG emissions (for a review see, e.g., [1]). Conversely, uncertainties in technological developments have—with notable exceptions—so far received less attention. Frequently, scenario studies embrace an incrementalist view of future technology and anticipate no radical changes. The major mechanism of technological change is the assumed progressive depletion of conventional oil and gas resources, which in most scenario studies triggers a massive return to coal and, hence, a high GHG emission (and climate change) future (for a discussion see [2] and [3]). In this article we illustrate that uncertainties in technological developments appear as important as uncertainties in demographic and economic developments in terms of their influence on future GHG emissions.

This article presents one part of collaborative work undertaken by an international team of researchers to explore the uncertainties inherent in projecting GHG emissions over the next century (see Nakicenovic's Introduction to this issue). In this article we illustrate how the large uncertainties of alternative developments in technology translate into a wide range of future GHG emission levels, which in turn result in different climate change impacts. To this end, we explore possible multiple pathways of technological change within one scenario family, the high growth cases of the A1 scenario. We then explore the feasibility and costs of policy scenarios that meet the stated objective of the United Nations Framework Convention on Climate Change of "stabilization of GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" [4]. Because at present scientific uncertainty is very great regarding what exact level constitutes a "dangerous interference with the climate system," calculations are reported for a range of alternative CO_2 concentration stabilization targets at 750, 650, 550, and 450 ppmv. We conclude with a discussion of analytical and policy implications of our analysis.

The most distinguishing feature of the A1 (also labeled "High Growth") scenario family (see also Morita et al. in this issue) is that the scenario explores a future in which present development gaps between "rich" and "poor" (or between the developed and the developing countries) largely disappear. This (normative) scenario assumption was made in response to the critique that the earlier Intergovernmental Panel on Climate Change (IPCC) scenarios insufficiently explored this possibility and, hence, were "unfair" to the South [5]. The 1994 evaluation of the IPCC IS92 long-term GHG emission scenario series also concluded on the need to "explore a variety of economic development pathways, for example, a closing of the income gap between industrialized and developing regions" [1]. Consistent with both historical evidence as well as growth theory, income growth and a reduction of per capita income differences basically imply growth in *productivity* and equalization of productivity differences across different economies in which technological change (along with education and institutional factors) plays a central role (for a review of historical evidence see, e.g., [6]; for recent cross-country evidence see, e.g., [7]; for a review of growth theory see, e.g., [8]). Consistent with the observation that technological change is crucial for productivity growth, high rates of technological change are explored in the scenario family A1 that is characterized by high (macroeconomic) productivity growth.

The systemic and cumulative nature of technological change lead to clustering effects (technological interdependence) and possible phenomena of increasing returns (i.e., the more a technology is applied the more it improves and widens its market potentials). Combined, they explain both the pervasive impacts of technological change, once implemented, but also the considerable inertia to implement change due to "lock-in" effects [9, 10]. Related concepts of path dependency (change goes in a persistent direction based on an accumulation of past decisions) help to explain the intriguing stability of technological change trajectories at the macro level (see, e.g., [11, 12, 13]). As a result, technological change can go in multiple directions, but once change is initiated in a particular direction, it becomes increasingly difficult to change its course. Research development and demonstration (RD&D) as well as investment decisions in the energy sector over the next two to three decades are consequently critical in determining which longer-term technological options in the energy sector may be opened, or which ones may be foreclosed [14]. The scenarios reported here illustrate such alternative technology futures of the energy sector due to alternative technology and resource development strategies.

Four variants of the A1 scenario family are presented in this paper. They were created with the MESSAGE energy systems model at the International Institute for Applied Systems Analysis (IIASA). Huge energy demands and large uncertainties about future technology use and technology dynamics, lead to a potentially large range of CO_2 emissions from 5 to 34 GtC in 2100, and CO_2 concentrations of 560 to 950 ppm in 2100. Varying the technology assumptions within the High Growth A1 scenario family in fact translates into a range of future CO_2 emissions as large as the range spanned by the literature CO_2 emissions presented in Kram et al. (in this issue), which explore additional uncertainties in demographics, economy, and environmental policy. In other words, decisions that could lead the global energy system into alternative directions, e.g., either to a massive return to coal or, alternatively, on a pathway of continued "decarbonization" [2], matter as much as decisions on a particular long-term climate policy target, for example, in the form of CO_2 concentration stabilization levels.

The remainder of this article is as follows: The following section describes commonalities and differences between the four A1 baseline scenarios. They share similar energy demand and economic and population developments, but differ mainly in assumptions on technology dynamics and resource availability. This highlights, in particular, differences of CO_2 stabilization costs as a function of baseline uncertainties. The baseline scenarios include a coal intensive scenario (A1C), an oil and gas intensive scenario (A1G), a "balanced" scenario with technological progress across the board (A1B), and a rapid technological change scenario toward post-fossil alternatives (A1T). The section also includes a note on how we deal with technological progress in the energy systems model. A later section, Atmospheric CO_2 Stabilization Cases of the Four A1 Baselines, describes the results of developing 450, 550, 650, and 750ppm atmospheric CO_2 stabilization cases from these four baselines. The final section presents conclusions and policy implications from our analysis.

A Set of High Growth A1 Baseline Scenarios

The A1 scenario family describes a case of rapid and successful economic development, in which regional differences in per capita incomes gradually disappear over the next century, making current distinctions between "poor" and "rich" regions largely obsolete. By and large, the A1 scenario implies a replication of the post-war growth experience of Japan and South Korea or the recent economic development of China on a global scale (see Appendix for a qualitative description of the scenario's "storyline" developed by the writing team). A replication of the most successful historical examples of industrialization and narrowing of income gaps on a *global* scale is without historical precedent. The resulting scenario may be considered as daring, or "unrealistic," by many. Yet, its implied high rates of macroeconomic productivity growth make it an ideal basis to explore high rates of technological change in the energy sector leading

TABLE 1
Overview of Main Commonalities in Scenario Drivers and Results of the Four A1 Baseline Scenarios Created with the MESSAGE Model (See [15]; and Riahi and Roehrl in this issue)

Commonalities of A1 baseline scenarios (A1B, A1G, A1C and A1T)	Results
Population in billions	Low IIASA [16] 8.7 billion by 2050 and 7.1 billion by 2100
Economic growth gross world product (GWP) (at market exchange rates)	Very high 1990–2020: 3.3% 1990–2050: 3.7% 1990–2100: 3.0%
Per capita income, GWP/cap in US$/GDP (at market exchange rates)	Very high In 2100: US$ 109,500 in Annex I, US$ 69,800 in Non-Annex I
Final energy use (annual)	High Increase from 275 EJ in 1990 to 1,743–1,769 EJ by 2100 for A1B, A1G and A1C. 1,270 EJ in A1T by 2100.
Land-use change[a]	Low 1990–2100: −3% of cropland, +6% grasslands and −2% of forest area

Notes: The classification (low, high, very high) is taken relative to the scenario literature. Differences in scenario drivers and results of the four A1 baselines are summarized in Table 2.
[a]Land-use data for the IIASA runs taken from AIM A1 land-use emulation runs.

to massive long-term structural changes in alternative directions and, hence, of technological uncertainty on future GHG emissions.

Four of these alternative pathways, according to different resource and technology development assumptions, are presented here as A1 baseline scenarios:

- A1C: "Clean coal" technologies that are generally environmentally friendly with the exception of GHG emissions;
- A1G: "Oil and gas"-rich future, with a swift transition from conventional resources to abundant unconventional resources including methane clathrates;
- A1T: "Post-fossil" future, with rapid development of solar and new nuclear technologies on the supply side, and mini-turbines and fuel cells used in energy end-use applications;
- A1B: "Balanced technology" future, exploring a combination of developments of the A1C, A1G and A1T scenario variants; the scenario assumes "balanced" progress across all resources and technologies from energy supply to end use.

Tables 1 and 2 summarize commonalities and differences between these four baseline scenarios. These are described in more detail in the following sections. They show an especially large range of GHG emissions. This range is of the same order of magnitude as the range spanned by all the new scenarios illustrated in this issue which explore other salient long-term uncertainties in demographics, economics, and environmental policy. Combined, the scenarios illustrate the large uncertainties of scenario baselines. They also illustrate the fact that similar GHG emission levels may be reached with very different combinations of input assumptions. Conversely, possible environmental burdens (such as climate change impacts and regional acidification) in the high growth

TABLE 2

Overview of Main Differences in Scenario Drivers and Results of the Four A1 Baselines Created with the MESSAGE Model (See Riahi, Roehrl in this issue; and [15])

	Cumulative hydrocarbon resource use (1990–2100)	Technology improvements				Primary energy use (by 2100)	Emissions (by 2100)		
		Coal	Oil	Gas	Nonfossil		CO_2[a]	CH_4	SO_2
A1B	Oil: Medium, 25.4 ZJ Gas: High, 31.3 ZJ Coal: Low, 19.7 ZJ	High	High	High	High	Very high, 2,681 EJ Low energy intensity of 4.9 MJ/US$	Median, 14.0 GtC Cumulative (1990–2100): 1,517 GtC	Medium 351 $MtCH_4$	Low 29.1 MtS
A1G	Oil: High, 34.5 ZJ Gas: Very high, 50.3 ZJ Coal: Low, 19.8 ZJ	Low	Very high	Very high	Median	Very high, 2,715 EJ Low energy intensity of 4.9 MJ/US$	High, 27.7 GtC Cumulative (1990–2100): 1,872 GtC	High 421 $MtCH_4$	Medium 38.4 MtS
A1C	Oil: Medium, 18.5 ZJ Gas: Medium, 20.5 ZJ Coal: Very high, 48.4 ZJ	High	Low	Low	Low	High, 2,325 EJ Low energy intensity of 4.2 MJ/US$	High, 32.7 GtC Cumulative (1990–2100): 1,999 GtC	Very high 668 $MtCH_4$	Peak in 2040: 129 MtS, declining to 46.8 MtS by 2100
A1T	Oil: Medium, 20.8 ZJ Gas: Medium, 25.0 ZJ Coal: Very Low, 11.7 ZJ	Low	High	High	Very high	High, 2,021 EJ Very low energy intensity of 3.7 MJ/US$	Low, 4.9 GtC Cumulative (1990–2100): 1,076 GtC	Low 269 $MtCH_4$	Very low 17.2 MtS
Marker scenario range	Oil: 16.1–19.5 ZJ Gas: 14.6–36.1 ZJ Coal: 12.2–38.6 ZJ					551–2079 EJ, 2.0–7.1 MJ/US$	5.7–29.1 GtC	236–889 $MtCH_4$	25.9–60.3 MtS

Notes: The classification (low, medium, high, very high) reviews technology dynamics across the MESSAGE-A1 baseline scenarios relative to the scenario literature. A summary of technology improvements for extraction, distribution, and conversion technologies assumed for the A1 baseline scenarios is also included. The "marker scenario range" illustrates the range of the B2 (Riahi and Roehrl, in this issue), A1 (Morita et al. in this issue), B1 (de Vries et al., in this issue) and A2 (Sankovski et al., in this issue) scenarios described in this issue which are very different in terms of economic, demographic and technological assumptions.

[a] CO_2 emissions from fossil fuels and industrial processes.

A1 world might range from disastrous to relatively benign, depending essentially on rates and directions of technological change.

COMMONALITIES: POPULATION AND ECONOMIC DEVELOPMENT AND RESULTING ENERGY DEMAND

In the A1 scenario family, demographic and economic trends are closely linked, as affluence is correlated with long life and small families (low mortality and low fertility). The population trajectory assumed is based on a variant of the low population projection reported by Lutz et al. [16, 17], combining low fertility with low mortality and central migration rate assumptions. After peaking at 8.7 billion in the middle of the next century, world population declines to 7.1 billion in the year 2100 (see Table 1). The assumption of below-replacement fertility levels results also in a significant population aging, which in the long-term affects all world regions.

The scenario family A1 explores a world in which future economic development follows the patterns of the most successful historical examples of economic development catch-up. Free trade, continued innovation, and a stable political and social climate enable developing regions to access knowledge, technology, and capital. The global economy is projected to expand at an average annual rate of 3% to 2100 (see Table 1), roughly in line with historical experience over the last 100 years [18]. The 3% per year economic growth rate translates into a 26-fold expansion of global economic output[1] that would reach US$550 trillion by 2100. As a byproduct of rapid economic development and a fast demographic transition, income inequities between Annex I and non-Annex I countries[2] are reduced to almost zero. Per capita income ratios would be 1:1.6 in 2100, compared to a ratio of 1:16 in 1990. Per capita income in Annex I increases to about US$109,000, and in non-Annex I countries to US$70,000. By and large, the A1 scenario implies a replication of the post-war experience of Japan and South Korea, or the recent economic development of China across all developing regions.

Other commonalities of all A1 variants are relatively high energy demand (see Table 1), moderated, however, by continuous structural change and the diffusion of more efficient technologies, consistent with the high productivity growth and capital turnover rates. In the A1B, A1C, and A1G scenario, improvements in energy efficiency on the demand side are assumed to be roughly in line with historical experience. These improvements may be considered to be relatively low compared to more "green" scenarios (see, e.g., the B1 scenario in de Vries et al. in this issue). Low energy prices provide little incentive to improve end-use energy efficiencies, and high income levels encourage comfortable and convenient (often energy-intensive) lifestyles. Efficient technologies are not fully introduced into the end-use side. However, the A1T scenario explores some of the consequences of an increased final to end-use efficiency. All A1 variants, however, share a similar demand for energy *services*.

MULTIPLE BRANCHING IN TECHNOLOGY DYNAMICS AND RESOURCE AVAILABILITY

Figure 1 illustrates the change of world primary energy structure over time. The historical change reflects major technology shifts, from traditional use of renewable

[1] Throughout this article, GDP and GDP-related numbers are presented at market exchange rates and in 1990 US$.

[2] The 1997 Kyoto Protocol to the FCCC lists developed countries in "Annex I." All other countries are referred to as Non-Annex I countries.

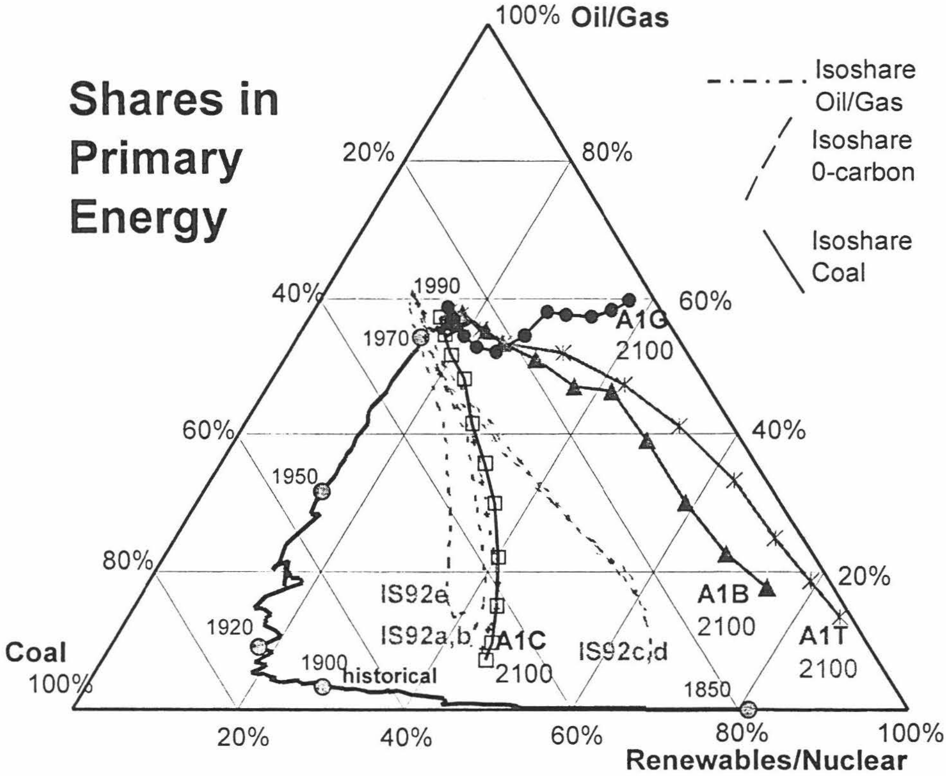

Fig. 1. Global shares in primary energy use, coal, oil/gas and nonfossil energy, illustrated with an "energy triangle" (in percent). Constant market shares of coal, oil/gas, and nonfossil (zero-carbon) energies are denoted by their respective isoshare lines. Historical data from 1850 to 1990 are based on [14]. For the years 1990–2100, alternative trajectories for the four A1 scenario variants, A1B, A1T, A1G, and A1C unfold. For comparison, the IS92 scenario series are also shown, clustering along two trajectories (IS92c,d and IS92a,b,e,f respectively). Bullets on the 1990–2100 trajectories represent 10-year time steps.

energy flows to the coal and steam age of the 19th century[3] to the dominance of oil and internal combustion engines in the 20th century. Around 1850, only about 20% of world primary energy was provided by coal, the other 80% was provided by traditional renewable energies (biomass, direct wind and hydropower, and animal and human energy). With the rise of industrialization, coal substituted for traditional renewable energy forms, and by 1920, around three-quarters of world primary energy use relied on coal. The second major transition was the replacement of coal by oil and later by gas. By the early 1970s, 56% of global primary energy use was based on oil and gas. Since then, the global primary energy structure has changed little, efforts to substitute for oil imports have led to a certain revival of coal and to the introduction of nonfossil alternatives in the Organization for Economic Cooperation and Development (OECD)

[3] With a resulting dominance of coal, peaking around the 1920s.

countries (e.g., nuclear energy in France). Rapid growth in energy demand and coal use, particularly in Asia, have outweighed energy structural changes in the OECD countries.

Alternative, possible future evolutions of the global primary energy structure[4] from 1990 to 2100 are illustrated with the four A1 baseline scenarios. For these scenarios, we assume technological change in energy conversion and supply technologies to be strongly interrelated. Therefore, resource availability in each of the scenarios depends on the alternative investment strategies into exploration, production, and conversion technologies.[5] These result in alternative transition strategies away from conventional oil and gas [including the A1G scenario in which the large geological occurrences of unconventional oil and gas (for a review see [19]) can be tapped]. Figure 1 illustrates this multiple branching in the evolution of global primary energy structures of the different A1 baseline scenarios from 1990 to 2100. A1B, and even more so, A1T, follow a trend toward increasing shares of zero-carbon options in the long term. A1G more or less follows an oil/gas isoshare line, perpetuating the current dominance of oil and gas in the global energy balance far into the 21st century. A1C indicates a near doubling of coal's share in primary energy use. This evolution is path dependent. In the section on Atmospheric CO_2 Stabilization Cases, the four A1 scenario variants are used as baselines for discussing CO_2 abatement costs for meeting alternative long-term climate change stabilization targets.

The following five sections describe resource availability and technology improvement assumptions that define the four different A1 baselines in more detail.

Coal-Intensive Baseline—A1C

The high growth, coal-intensive scenario A1C illustrates the long-term GHG emission implications of quickly "running out of conventional oil and gas" combined with slow progress in developing alternatives, except for progress in coal-related technologies. It assumes relatively high cost improvements in new and clean coal technologies such as coal high-temperature fuel cells, integrated coal gasification combined cycle power plants (IGCC) and coal liquefaction. Only modest assumptions are made for all other technologies, except for nuclear technologies (including uranium extraction technologies), which in the A1C scenario are significantly developed towards the end of the 21st century, when zero-carbon options are needed to ease the resource and environmental constraints of a coal-intensive economy. In terms of resource assumptions, A1C is restricted mainly to availability of currently assessed quantities of conventional oil and gas which results in the low cumulative oil and gas use of 39 ZJ (1 ZJ is 10^{21} Joules.) and very high cumulative coal use of 48 ZJ between 1990 and 2100 (see Table 2).

Whereas final energy use in A1C is similar to that of A1B and A1G, total primary energy is lower since A1C makes use of advanced clean coal technologies, such as coal high temperature fuel cells with very high efficiencies. In 2100, the main primary energy

[4] In this article, we adopt as primary energy accounting methodology the direct equivalent method for all nonthermal uses of renewables and nuclear. For instance, the primary energy equivalence of electricity generated from solar photovoltaics or nuclear power plants is set equal to their respective gross electricity output and *not* the heat equivalent of radiation energy from fissile reaction, the solar radiance falling onto a photovoltaic panel and converted to electricity (with efficiencies ranging from 10 to 15%), or the heat that would have to be generated by the burning of fossil fuels to produce the same amount of electricity as generated in a photovoltaic cell or a nuclear reactor (which would be the so-called "substitution" accounting method).

[5] As outlined in the section Representation of Technological Progress on the MESSAGE model, time profiles of costs of energy conversion and supply technologies are direct input assumptions. Reserves/resources are split in different cost categories following [19]. In other words, we *chose* consistent resource and technology assumptions, they are not output of the model.

carrier is coal which has a share of 1,084 EJ (47%), but all of that coal is converted to high quality fuels demanded by the affluent consumers of the 21st century. Demand for coal is so large that some world regions run out of coal, whereas large coal occurrences remain available in the former Soviet Union, North America, and to some extent, China. Therefore, a large-scale global methanol trade unfolds. In 2100, the transport sector, for example, depends on methanol produced from coal for 64% of its energy use. Some coal-poor regions try to rely increasingly on nuclear technologies to ease their import dependence. On the global level, this leads to an important share of nuclear[6] (18%) in the primary energy supply. Thus, even assuming that technological change unfolds in the direction of "clean coal" technologies, coal remains more of a regional fuel that needs to be complemented by alternatives.

Oil- and Gas-Intensive Baseline—A1G

The high growth oil and gas-intensive scenario A1G illustrates long-term GHG emissions under the assumption of rapid technological progress for extraction and conversion technologies of oil and gas (conventional and unconventional). In addition to the improvement and extension of present oil and gas grids and transportation/distribution infrastructure, new natural gas pipelines from Siberia, the Caspian, and the Middle East to China, Korea, Japan, and South Asia (India) are introduced in the scenario after 2010/2020 [20].[7] It is assumed that extraction and refining technologies for oil and gas experience rapid improvements so that the extraction of natural gas hydrates and of unconventional oil like oilshales or natural bitumen (tarsands) becomes economically feasible on a large scale beyond current niche market applications (Canada and Venezuela). This leads to a world dominated first by oil and later by gas as primary energy fuels. Since unconventional oil and gas resources are distributed unevenly over world regions, there is large-scale gas and oil trade, mainly from the former Soviet Union and the Middle East. Cumulative oil and gas extraction from 1990 to 2100 amounts to 85 ZJ (see Table 2), about twice as high as in A1C. A1G reflects current perceptions that radical technological change would need to occur in order to translate a more significant portion of the geological resource base of unconventional oil and gas into technically and economically recoverable reserves, a development evidently also cross-checked by possible developments in nonfossil alternatives. Although there is less conversion than in the other A1 scenarios, and final energy demand is of the same magnitude as that of A1B and A1C, world primary energy use in A1G is high because of additional energy requirements for the extraction of shale oil and methane clathrates and for gas transport over continental distances. Because of large capital turnover rates in A1G, primary energy needs per unit of gross domestic product (GDP) improve somewhat faster than the historical experience. The main primary energy carriers in 2100 are natural gas (45%), oil (14%), nuclear (12%), and renewables (25%). Again, as was the case in the A1C scenario reported above, nonfossil alternatives supplement the oil and gas intensive energy menu of the A1G scenario due to the uneven distribution of conventional and unconventional oil and gas resources.

[6] Here and thereafter when we refer to "nuclear" we assume possible new generations of inherently safe nuclear reactors. These may be relatively small size, and highly standardized types. Due to large political uncertainties of societies' acceptance of future nuclear technologies, however, the category "nuclear" in our scenarios may be regarded as a placeholder for other future zero-carbon electricity base load technologies.

[7] Initial financing requirements for such a Russian gas grid might be eased by global CO_2 trading under the 1997 Kyoto protocol, which might generate annual financial inflows of US$15-$20 billion to Russia.

Rapid Technology Change, Post-Fossil Baseline—A1T

The high growth "post-fossil" A1T baseline explores long-term GHG emissions in case of very rapid technological change for nonfossil alternatives. Large-scale and targeted RD&D investments are a prerequisite for such a scenario. A1T, for instance, would imply the large-scale installation of new, inherently safe and cheap nuclear technologies (e.g., high temperature reactors) and new renewable technologies. Another difference to the other three A1 baselines is that A1T explores further final to end-use efficiency improvements resulting in the same useful energy but lower final energy (1270 EJ in 2100, see Table 1[8]). A1T assumes medium levels of resource availability for oil and gas (90 ZJ). However, because of fast technological progress in post-fossil alternatives, cumulative oil and gas extraction (46 ZJ) and coal extraction (12 ZJ) from 1990 to 2100 remain small in comparison to the other scenario variants. In 2100, the main primary energy carriers are renewables and nuclear (86%), and natural gas 196 EJ (10%). The shift toward carbon-free and also decentralized technologies is nearly complete in all world regions by 2100.

"Balanced Technology" Baseline—A1B

The high growth "balanced technology" A1B baseline explores "balanced" progress across all resources and technologies from energy supply to end use. Investment costs for electricity generation with solar photovoltaic decrease by a factor of more than ten, those for fuel cells, hydrogen, and wind technologies by a factor of two to five, and those of new nuclear technologies by a factor of one to three. Liquid fuels from coal or unconventional oil/gas resources become available at less than US$30 per barrel, with costs falling further by about 1% per year with exploitation of learning curve effects. Nonfossil electricity (photovoltaics, new nuclear) become available at costs of less than 10 mills/kWh (0.01$/kWh), and continue to improve further (perhaps as low as 1 mills/kWh). Energy resources are taken to be plentiful by assuming large reserves of unconventional oil and gas, and high levels of improvement in the efficiency of energy exploitation technologies, energy conversion technologies, and transport technologies. This results in initially large hydrocarbon use (see Table 2), which is later increasingly substituted by zero-carbon options. Contrary to the other scenario variants in which technological change in the energy sector is largely "path dependent," the A1B scenario variant presupposes some sort of coordination mechanism in technology RD&D allowing regions/countries to specialize in the development of alternative technology clusters (e.g., "clean coal," nuclear, or renewables) and their subsequent effective diffusion and transfer at the international level.

Representation of Technological Progress in MESSAGE

As outlined in the last sections, the A1 baseline scenarios mainly differ in their assumptions on technological progress. This section summarizes how processes like technological learning are taken into account in the MESSAGE model (version IV, see also [15]; and Riahi and Roehrl in this issue, pp. 175–205) used to quantify the scenarios described in this article. The evolution of technological knowledge is among

[8] The increased final to end-use efficiency in A1T as compared to the other A1 baselines is a consequence of the assumption of rapid technological change in A1T. A1T experiences a shift to radically different energy conversion technologies as compared to today. These provide *high quality fuels* such as electricity and H2 on the final energy level. Conversion from final energy to end-use energy services is, therefore, possible with very high efficiencies (e.g., with H_2 fuel cells). Furthermore the use of the direct equivalent method (see footnote 1) increases the final to end-use efficiency further because of the use of decentralized technologies such as decentralized solar thermal technologies in the residential sector.

the main drivers of long-term productivity and economic growth [18]. Over long time horizons, performance of technologies is considerably improved (efficiencies increased, unit costs reduced, etc.) and new technologies are introduced.

MESSAGE IV is a linear programming model (LP) of the global energy systems model operating on 11 world regions. It minimizes total discounted system costs for 1990–2100. For the scenarios featured in this article, technical, economic and environmental parameters for over 400 energy technologies (out of a set of 1,600 in the CO2DB database [21]) are specified explicitly in the model. Technological learning is a classical example of increasing returns; that is, the more experience accumulated by organizations and individuals, the better the performance and the lower the costs of a technology. Unit costs typically decrease exponentially as experience (measured as a function of cumulative output) is gained. This decay reflects that learning itself shows decreasing marginal returns. Learning curves are characterized by a single learning rate and initial unit costs. Assuming fixed learning rates ex ante in the model formulation is, however, not possible within an LP formulation, because it is a nonconvex problem which has to be tackled, for example, with Mixed Integer Programming (MIP). Illustrative MIP versions of MESSAGE to endogenize technological change through uncertain returns from research and developent (R&D) and learning have been developed [22], but are computationally infeasible for a detailed scenario that includes over 400 energy technologies and operates on 11 world regions, as in the A1 cases here.

For our purposes, we use an iterative approach here. In MESSAGE IV, we treat technology exogenously, that is, performance of technologies improves at predefined rates over time. MESSAGE solves for the global minimum of discounted total costs for a fixed model time horizon. The assumed time profile of unit costs will, at first, not necessarily follow the exponential decay behavior. However, in an iterative fashion, we tried to make the ex ante assumed time profiles of cost reductions for new installations consistent with the resulting time profiles of cumulative installed capacities (at least for major technologies). This approach is made possible with additional dynamic market penetration constraints in order for the most important technologies to avoid "flip-flop" behavior, and to emulate the initial slow growth in niche markets of newly introduced technologies due to upfront investments.[9] Figure 2 shows examples of resulting cost decrease curves versus cumulative installed capacities in the A1B baseline scenario. Since investment costs as a function of cumulative installed capacities follow power laws, they appear as straight lines when plotted with logarithmic axis. All in all, Figure 2 illustrates that in our scenario the unit costs for main technologies follow roughly this power law dynamics.

Compared to historical experience [13], the resulting learning rates in the A1B and A1T scenarios are on the optimistic end. For example, the learning rate for photovoltaic power plants in the A1B baseline scenario is nearly 35%, that is, cost reductions of 35% per doubling of cumulative installed capacity. This is a learning rate comparable to estimated historical learning rates from 1973 to 1995 for photovoltaic cells in Japan as reported by Watanabe [23, 24] and somewhat higher than the historical experience in the United States and Europe [13].

[9] In reality, initial applications of new technologies in niche markets have the benefit of leading to early cost reductions because of learning effects. Our LP model formulation, however, would not "need" this initial learning as long as additional dynamic market penetration constraints force the model to do early investments to be able to install large capacities later.

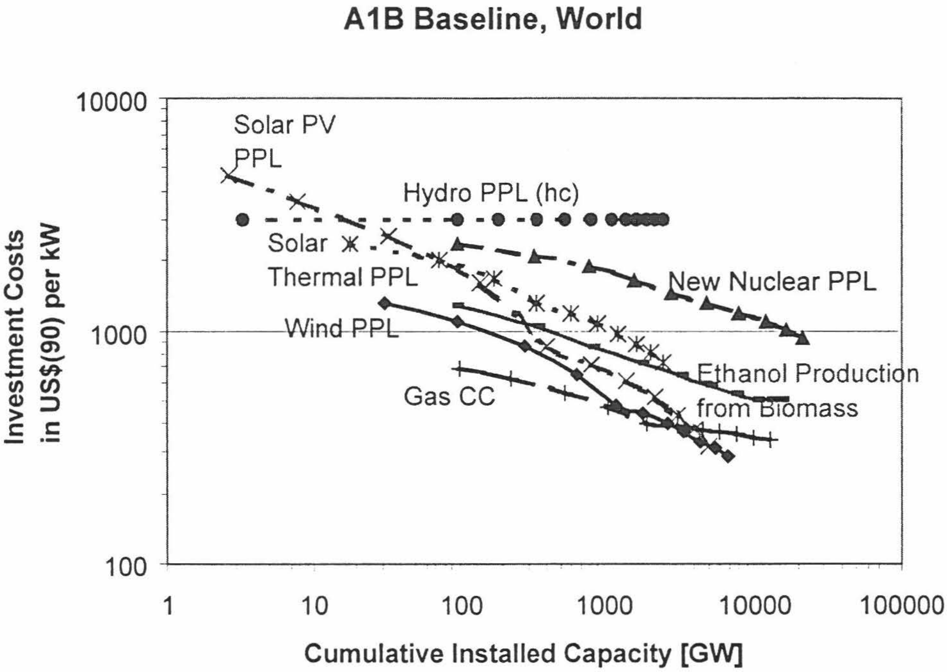

Fig. 2. Examples of learning curves in the A1B baseline scenario (1990–2100) as implemented in MESSAGE IV. Investment costs as a function of cumulative installed capacities follow power laws. Plotted with logarithmic axis they appear as straight lines. Abbreviations: PV: photovoltaic; PPL: power plant; Gas CC: gas combined cycle power plant; New Nuclear PPL: future design of a new nuclear reactor.

CO_2 EMISSIONS—A1 BASELINES

As explained above, different technology dynamics in the different A1 baseline scenarios result in diverging energy supply structures and, hence, a large range of future CO_2 emissions (see Figure 3). This range is comparable to the range of the IPCC IS92 scenario series [25] that explored mainly the uncertainties in demographic and economic developments and paid less attention to technology dynamics [2]. The CO_2 range of the A1 baselines is also comparable to that of all the scenarios presented in this issue. The CO_2 emission trajectories of the oil and gas-intensive A1G, and the coal-intensive A1C, exhibit continuously increasing CO_2 emissions, reaching 28 and 33 GtC, respectively. This is, however, still lower than the CO_2 emissions of 40 GtC that one would expect from a simple extrapolation of the 1990 energy structure in line with the A1 energy demand increase. A1B and A1T show a different CO_2 emissions behavior. Due to the inertia of the energy system, CO_2 emissions increase initially, show a peak in the middle of the next century, and then start to decline to 14 and 5 GtC, respectively, in 2100 due to technology-induced structural change.

We also include, in addition to the dominant energy-sector emissions, CO_2 emissions from industrial sources and land use changes,[10] to estimate resulting atmospheric CO_2 concentrations for the four A1 baselines (see Figure 4). These were calculated using

[10] Land use emissions were estimated using land use change data from AIM runs of the IPCC SRES A1 marker scenario. For the purpose of this article, we do not derive different land use change data for all the different CO_2 stabilization cases due to non-availability. In other words, we only analyze CO_2 abatement measures in the energy system.

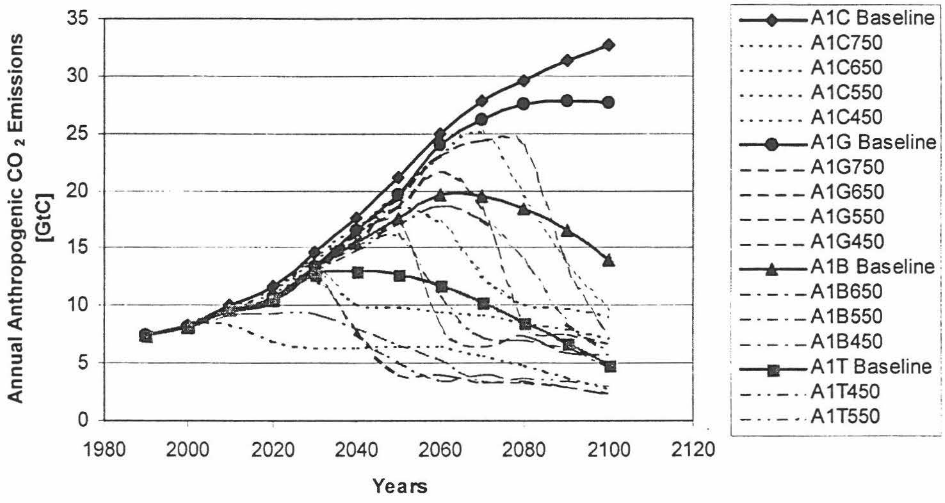

Fig. 3. Annual anthropogenic CO_2 emissions for the four A1 scenario baselines. Thin lines indicate emissions for alternative concentration stabilization scenarios calculated on the basis of the four A1 scenario baselines (in GtC).

the MAGGIC (Model for the Assessment of Greenhouse-gas Induced Climate Change, version 2.3) model [26]. The resulting CO_2 concentrations in 2100 range from 560 (522–601)[11] ppmv in A1T, to 724 (670–776) ppmv in A1B, to 891 (825–951) ppmv in A1G, to 950 (880–1012) ppmv in A1C (see Figure 4). These atmospheric CO_2 concentrations are "best guess" model parameterizations.[12]

Atmospheric CO_2 Stabilization Cases of the Four A1 Baselines

In the previous section we have illustrated the sensitivity of the magnitude of future GHG emissions and, hence, of possible climate change to rates and direction of future technology change in the energy sector. Based on current understanding, climate change implied especially by our high emission scenarios could be substantial and adverse to both humankind and natural ecosystems [27]. Hence, we explore alternative policy scenarios congruent with the stated objectives of the FCCC, that is, the "stabilization of GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." Because scientific uncertainty at present precludes an exact quantification of what a "dangerous" level would constitute, we perform a sensitivity analysis for a range of stabilization targets (derived from IPCC [27]).

POSSIBLE CO_2 MITIGATION STRATEGIES

The largest anthropogenic contributor to global warming is CO_2. Strategies to stabilize the atmospheric CO_2 concentration may be based on technological change, or they may be based additionally on economic incentives and institutional frameworks. They range from using the carbon sequestering potential of afforestation to demand-

[11] Numbers in the brackets show corresponding uncertainties due to carbon cycle uncertainties.

[12] Model parametrizations used to calculate CO_2 concentrations here are similar to those used by the IPCC in their Second Assessment Report [27].

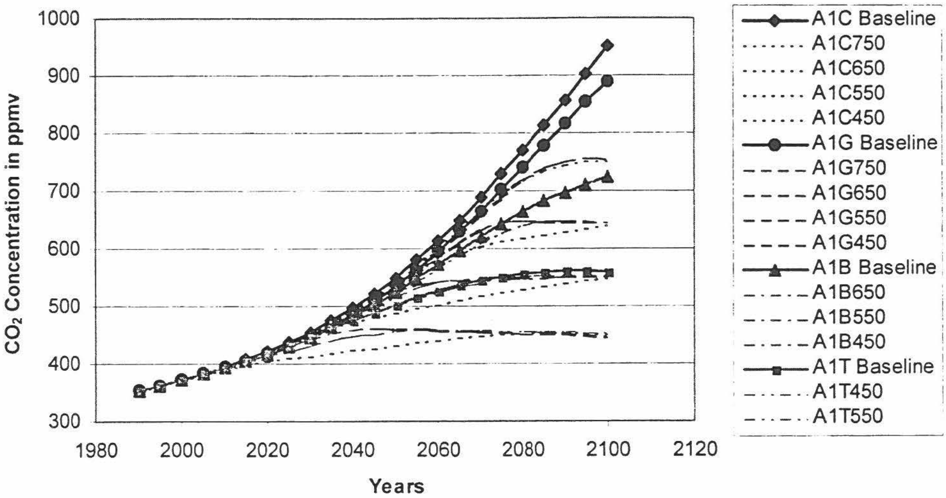

Fig. 4. Atmospheric CO_2 concentrations for the four A1 baseline scenarios. Thin lines indicate concentrations for alternative concentration stabilization scenarios calculated on the basis of the four A1 baseline scenarios (in ppmv).

side or supply-side oriented measures in the energy sector and even so-called geo- and cosmo-engineering [12].[13]

For simplicity, in this article we analyze atmospheric CO_2 concentration stabilization cases only and confine our discussion to CO_2 abatement measures in the *energy sector* (see the following section, Atmospheric CO_2 Stabilization Cases).

In the energy sector, there are many types of technological strategies for stabilizing and eventually reducing energy-related emissions including, for example, the incremental replacement of power plants to improve energy efficiency. For example, energy end-use is the least efficient part of the current energy systems and therefore has the highest potential for efficiency improvements [12, 14]. As illustrated over time in all A1 baseline scenarios, this might, in the long run, also induce changes of technological trajectories "upstream" (e.g., substitution of fuels using existing infrastructure) and eventually of the whole energy chain (e.g., change of infrastructure from extraction to energy services). An example is the evolution of lifestyles and subsequent changes in energy use patterns that trigger corresponding changes in energy supply systems.

A large number of strategies are often referred to as *"add-on" environmental strategies.* They include, for example, CO_2 removal by scrubbing and CO_2 recovery from flue gases. After recovery of CO_2 from the energy system, it has to be disposed of, stored or otherwise used. For example, in what is called enhanced oil recovery, CO_2 is injected in oil fields (originally to improve the oil recovery rate). CO_2 may be stored also in depleted natural gas and other underground reservoirs, eventually also in the deep ocean [28].

[13] The latter may be illustrated by the following consideration: About 10% of today's planet land area is actively managed. To compensate for a rise in global temperatures by reflecting a fraction of the incoming solar radiation; an albedo change of about 1% could compensate for about 1,000 GtC cumulative carbon emissions. Orbital shades might be as expensive as >\$55/tC, but suborbital shades may be as cheap as >\$0.1/tC. However, environmental effects of such large-scale measures are completely unknown so far.

Original natural gas *reserves* in place correspond to a potential storage capacity of about 150 GtC. With the extraction of higher gas categories, this storage capacity may be larger than at least 250 GtC. In 1996 the IPCC estimated the potential storage capacity of depleted oil and gas fields alone to be as high as 500 GtC [27]. Deep subterranean sandstone aquifers have a longterm CO_2 storage capacity of about 90 GtC. CO_2 is also stored in chemical feedstocks and basic materials, for example, CO_2 is used in the synthesis of urea (>10 MtC/year). A promising new method is the hydrocarb process [29] to produce methanol and carbon from biomass and fossil fuel with subsequent storage of carbon (very large volumes) in elemental form. A recent method developed by Steinberg [30] is the Carnol system, which consists of methanol production by CO_2 recovered from coal-fired power plants and natural gas, and the use of methanol as an alternative automotive fuel.[14] By far the largest reservoir for carbon disposal in form of solid CO_2 ice is the deep ocean, which currently stores about 36,000 GtC. The global carbon cycle involves annual exchange of about 200 GtC between the oceans, the atmosphere, and the biosphere, compared to about 6 GtC emissions from fossil fuel production and use.

ATMOSPHERIC CO_2 STABILIZATION CASES

The scenarios described in this section were developed with MESSAGE, a bottom-up energy systems model that incorporates mitigation technologies drawing on a technology inventory, CO2DB [21, 31, 32], developed at IIASA. The inventory contains information about technical characteristics of mitigation technologies, their cost structure, emissions, time horizon of their availability, etc. As explained in the previous section, we focus here on measures in the energy sector only.

This section discusses the CO_2 abatement measures in the energy sector to achieve CO_2 stabilization by 2100, starting with the four A1 baselines described earlier in the article. The stabilization levels have been set at 750, 650, 550, and 450 ppmv to facilitate comparison with the existing literature (see, e.g., [33]). Technically, we perform illustrative "inverse calculations," imposing an atmospheric CO_2 concentration stabilization constraint (by 2100) on the energy model MESSAGE which then calculates the intertemporal optimum (cost minimum, discount rate 5%) for meeting the constraint. In [3] the sensitivity toward changes in discount rate as well as to different model representations of technological change were analyzed. Consistent with the consideration of climate change as a global, and long-term, environmental externality problem, we assume full temporal and spatial flexibility of mitigation measures, that is, the model is free to choose emission reduction when and where it is cheapest to do so, consistent with the global constraint. We separate the issue of "who mitigates" from the issue of "who pays for mitigation." For instance, the model calculations are consistent with the existence of a global "carbon permit system," which internalizes the costs of the carbon externality into energy systems costs and, through global "permit" trading, could assure least cost implementation of emission reduction measures. Alternative emissions permit schemes that are likely to reflect the "common but differentiated responsibility" (FCCC, [4]) to the CO_2 externality were not analyzed for this article. A departure from the assumed temporal and spatial flexibility of emission reductions in the model would increase the costs of complying with a global CO_2 concentration target. Hence, our calculations

[14] Carnol System CO_2 Reduction: When methanol is used in automotive internal combustion engines, a CO_2 reduction by 56% compared to conventional system of coal plants and gasoline engines is achieved, and a CO_2 reduction by as much as 77% when methanol is used in fuel cells in automotive engines [30].

represent "least cost" solutions of dealing with a long-term global environmental issue, and these least cost solutions may be infeasible when facing political realities.

Our result confirms the CO_2 emission pattern of stabilization cases discussed by Wigley, Richels, and Edmonds [33]: Global emissions rise initially, then pass through stabilization in order to decline in the second half of the 21st century (see Figure 3). Absolute emissions in 2100 for a given CO_2 concentration target differ due to different emissions paths up to 2100 (see Figure 3). The stabilization issue may be approximately viewed as a carbon budget allocation problem, and for each stabilization level there is roughly a fixed allowable amount of CO_2 to be released. In other words, given a particular stabilization target, cumulative carbon emission between 1990 and the year 2100 are limited, between roughly 740 GtC for 450 ppmv to 1,700 GtC for 750 ppmv. Figure 4 shows the resulting atmospheric CO_2 concentrations.

To achieve CO_2 stabilization at a given level, CO_2 abatement in the energy sector is mainly reached through a mix of "add-on" technologies (scrubbers) and structural change in energy supply and, hence, technologies used in the energy sector. CO_2 scrubbers are an especially favored mitigation measure for the carbon-intensive baseline scenarios A1C and A1G (see Table 3). For the baseline scenarios A1B and A1T however, CO_2 abatement through structural change (i.e., change of energy technologies) is cheaper (see Table 3). The additional environmental constraint *accelerates* the aggregate rate of technological change already implicit in the scenario baseline. However, the share of scrubbing versus energy structural change is very sensitive to assumed scrubber costs. In particular for A1B and A1T, which assume considerable across-the-board technological progress, we also assume cost improvements for CO_2 scrubbers with increasing cumulative installations. Because of the large amounts of CO_2 scrubbed in stabilizing the high emission baselines A1G and A1C (see Table 3), estimates of CO_2 disposal costs were included in the calculations. Towards 2100 and with increasing amounts of scrubbed CO_2 such as in the 450 ppmv stabilization cases of the coal baseline A1C (see Table 3), it may become more and more difficult to store the increasing amounts of CO_2 without unacceptable environmental impacts (see the section on Possible CO_2 Mitigation Strategies and Table 3).

To achieve atmospheric CO_2 concentration stabilization, changes in the energy chains relative to the baselines are modeled on the level of individual technologies and in their ensemble of energy systems in MESSAGE. As explained below, changes occur mainly in the power generation sector and via a switching of energy fuels in the transport and the residential commercial sector.

For the *coal-intensive A1C* baseline, CO_2 stabilization by 2100 is achieved mainly through scrubbing in the second half of the 21st century. Because of the high level of affluence in A1, the transport sector becomes the dominant final energy sector. In A1C, increased individual mobility leads to an increased demand for methanol synthesized from coal. This, in turn, leads to a per capita energy use level in transport by 2100 in *all* world regions that is comparable to the per capita energy use in transport in the United States in 1990. Therefore, scrubbing in the stabilization cases for the A1C baseline occurs to a large extent at the level of methanol synthetic fuel production in addition to scrubbing in coal high temperature fuel cells which is the most widely used power generation technology in the A1C scenarios. The lower the CO_2 stabilization target, the larger the amount of methanol that is substituted by H_2 as a clean and carbon-free fuel. H_2 is mainly produced from nuclear high temperature reactors and via coal gasification and subsequent steam reforming of coal-based synthetic gas (with associated CO_2 capture and sequestration). Electricity demand is also satisfied increas-

TABLE 3

Summary Table of CO_2 Concentrations, Amounts of CO_2 Scrubbed (Divided in Reinjection and the Rest), and (Non-Discounted) CO_2 Abatement Costs in the Different A1 Scenarios

Scenario	CO_2 concentration	CO_2 concentration in 2100 (ppmv)	CO_2 reinjection 1990–2100 (GtC)	Other CO_2 scrubbing, 1990–2100 (GtC)	Total cumulative costs, 1990–2100 (trillion US(90)$)	Total cumulative investment costs, 1990–2100 (trillion US(90)$)	Total costs per final energy in 2100 ($/TJ)
A1B	Baseline	723	28	0	758	258	7.8
A1B650	Stabilized	650	70	103	762	261	8.0
A1B550	Stabilized	550	99	362	774	266	8.0
A1B450	Stabilized	450	98	762	795	272	8.1
A1G	Baseline	891	171	0	828	287	8.4
A1G750	Stabilized	750	295	170	836	289	8.8
A1G650	Stabilized	650	340	425	850	293	9.1
A1G550	Stabilized	550	357	729	870	297	9.2
A1G450	Stabilized	450	366	1148	898	304	9.3
A1C	Baseline	950	0	0	936	350	11.0
A1C750	Stabilized	750	48	357	965	367	11.8
A1C650	Stabilized	650	51	661	991	375	11.9
A1C550	Stabilized	550	68	926	1041	394	12.1
A1C450	Stabilized	450	63	1492	1319	499	14.5
A1T	Baseline (including stabilization)	560	29	0	553	188	6.8
A1T450	Stabilized	450	69	148	622	220	7.3

ingly through use of power generation with coal high temperature fuel cells, nuclear high temperature reactors, large wind/solar plants, and gas fuel cells.

For the CO_2 stabilization of the *oil and gas-intensive A1G* baseline, scrubbing is nearly as dominant as for A1C, but it occurs on a different technology mix. Huge demands for oil and gas, driven by economic growth and technological progress in gas extraction and conversion technologies, will—among other trends—also lead to maximization of extraction amounts from oil and gas fields. In the past, on average, only 34% of in situ oil and 70% of natural gas were recovered with primary (drive from initial reservoir pressure) and secondary (e.g., water or gas injection to compensate for declining reservoir pressure) recovery methods [19]. In the future, a considerable fraction of the original in situ oil and gas may be recovered from both abandoned and existing fields with advanced production technologies, such as CO_2 injection for enhanced recovery of oil and gas [12]. Considerable CO_2 emission reductions are possible if the use of gas combined-cycle power plants is increasingly complemented with CO_2 injection back into the depleted natural gas reservoirs. In the following, we will call the whole process "gas reinjection." In the A1G stabilization scenarios, increasing electricity demand is satisfied with ever more use of gas for electricity production. This is supplemented by increased H_2 cogeneration. In the transport sector, ethanol substitutes the use of gas. The lower stabilization cases of A1G also rely on increased synfuel scrubbing. The importance of hydrogen production, mainly from natural gas and to some extent via coal gasification, increases. Additional drastic energy structural changes will be needed in the 22nd century in order to shift away from the reliance on gas, especially because capacity limits of gas reinjection will be reached (see the section on Possible CO_2 Mitigation Strategies).

CO_2 stabilization of the *balanced technology A1B* baseline is achieved through a mix of CO_2 scrubbing and an acceleration of the scenario's inherent technology change dynamics toward nonfossil power generation and fuels. The lower the stabilization target, the larger the nonfossil electricity generation, in particular, in the form of increased use of new types of nuclear power plants, hydrogen fuel cell-based transport technologies and some additional (higher cost) hydropower plants. In addition, in power generation, more coal fuel cells substitute advanced coal power plants, and gas reinjection substitutes gas combined cycles. The transport sector sees especially H_2 (and electricity) as the main energy carrier instead of oil and gas. Most of this H_2 is produced with renewable technologies such as solar thermal power plants.

The rapid *technological progress A1T* baseline is so dynamic that it exhibits a CO_2 stabilization of 560 ppmv by 2100 without specific additional CO_2 control measures. The technology change patterns to achieve stabilization at lower CO_2 concentrations are similar to those of the A1B stabilization cases, but lead further into the post-fossil era. All in all, A1T and lower stabilization cases thereof illustrate the evolution toward *a hydrogen economy*. Except for gas reinjection, all other fossil power generation technologies are substituted by nonfossil power plants. Coal plays virtually no role in power generation. Most important are an increased use of nuclear high temperature reactors (for H_2 and electricity production) and hydrogen fuel cell-based transport (including decentralized off-hours electricity production). The dominating fuel in the transport sector and the residential commercial sector is H_2, which is produced with nuclear high temperature reactors and renewable technologies such as solar thermal power plants.

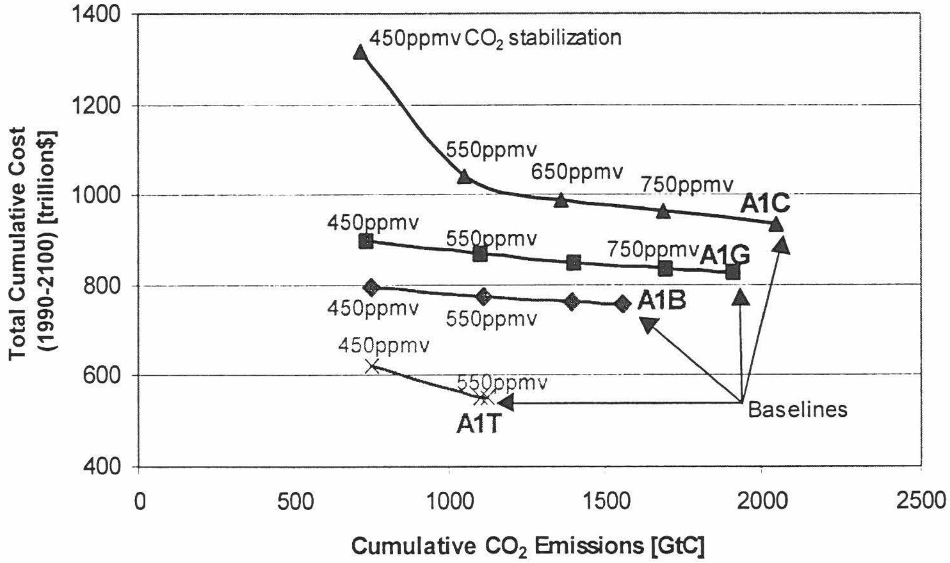

Fig. 5. Total (nondiscounted) cumulative system cost (1990–2100) vs. cumulative anthropogenic CO_2 emissions (1990–2100) for the baselines and, where applicable, respective CO_2 stabilization cases at 750, 650, 550, and 450 ppmv. This figure does not show any time resolution, each point depicts the outcome of one scenario over the entire 1990–2100 time horizon.

Table 3 illustrates that in the fossil A1 stabilization variants of A1C and A1G, large and increasing amounts of CO_2 are scrubbed.[15] Energy structural change will have to be accelerated towards nonfossil technology use especially after 2100, which will be very expensive in the cases derived from A1C and A1G because of large-scale technological lock-in in fossil-related technologies.

All the variants discussed here, in their energy technological mix, depend to a varying but considerable extent on power generation from nuclear technologies. This ranges from worldwide application of rather conventional nuclear power plants in A1G, A1C, and A1B, to even high temperature nuclear reactors with large-scale H_2 production in A1T.

Summary: Costs of CO_2 Abatement

Figure 5 (and Table 3) illustrate cumulative traditional investment costs for the global energy system from 1990 to 2100, that is, the sum of investment costs, fixed and variable operation and maintenance costs. We include capital requirements for energy production capacities, for conversion and transformation facilities, for transmission and distribution infrastructures, and for complying with environmental standards. However, we do not include investments in end-use technologies, such as furnaces, appliances and vehicles, because they are traditionally counted as durable consumer goods or business investment (see also [34]). Furthermore, we do not include investment requirements in R&D to achieve the assumed technology improvements in the scenarios. This is one of the reasons why the A1T baseline, which is very optimistic about technological progress in the end-use sector, seems almost like a "free lunch" (see Figure 5). Detailed

[15] In the 22nd century this might in turn lead to serious CO_2 storage problems (see section on Possible CO_2 Mitigation Strategies).

investment projections for end-use technologies and "R&D effectiveness," however, are difficult. On the other hand, simplistic order of magnitude estimates for R&D investments [35] and end-use technologies [34] indicates that the differences between these additional expenses (not covered in our analysis here) for the baselines discussed here are smaller than the differences between the traditional energy investments.

Total cumulative costs of the baseline scenarios and the respective atmospheric CO_2 concentration stabilization scenarios follow mainly from the assumed rates of technological progress. In increasing order of cumulative total costs, scenarios rank from A1T, A1B, A1G, to A1C. The total cumulative (1990–2100) costs for the baselines range by a factor close to two from about US$550 trillion (in 1990 prices) in A1T to US$940 trillion. The former being comparable to the global economic output of the A1 scenario by the year 2100. Cumulative CO_2 reduction costs (i.e., cost differences between baseline and respective stabilization scenarios) are lower than the cost differences from one baseline to another (see Figure 5).

These cumulative costs translate into the following average cumulative mitigation costs in US$ per ton carbon removed (relative to the respective baseline scenario):

- 750 ppmv: 25 $/tC for A1G750, and 61 $/tC for A1C750 (zero in the other scenarios);
- 650 ppmv: 19 $/tC for A1B650, 36 $/tC for A1G650, and 67 $/tC for A1C650;
- 550 ppmv: 33 $/tC for A1B550, 45 $/tC for A1G550, and 93 $/tC for A1C550;
- 450 ppmv: 43 $/tC for A1B450, 54 $/tC for A1G450, 182 $/tC for A1T450, and 258 $/tC for A1C450.

The CO_2 abatement costs of our calculations are of the same order of magnitude as those reported in the literature. For smaller CO_2 percentage cutbacks relative to the baselines, the CO_2 abatement costs discussed above are slightly lower but of the same order of magnitude as cost estimates from the GREEN model [36], the Edmonds and Barns model [37], and for the DICE model [38, 39]. Emission reduction costs are, however, much lower in our MESSAGE runs for the larger CO_2 percentage cutbacks relative to the baselines compared to the literature (e.g., [40]), due to the technology dynamics assumed in the MESSAGE runs. By and large this finding confirms earlier analysis [3] that cost differences for large percentage emission reductions are very sensitive to the technology dynamics underlying the (unconstraint) baseline scenario. Reduction costs are generally highest for scenarios with static technology.

The cumulative CO_2 abatement costs per ton carbon are highest in the coal baseline scenario A1C which is already the most expensive baseline in the A1 scenario set. In other words, a lock-in in a coal- and synthetic fuel-intensive energy system in the 21st century not only yields the most expensive energy system, it also yields the highest costs of meeting alternative climate stabilization targets.

How are these costs distributed over the time horizon from 1990 to 2100? Figure 6 shows total *annual* system costs per unit final energy over time. (Specific costs are shown to take into account the different level of energy end-use efficiency in the A1T scenario compared to the other scenario variants, costs comparisons on absolute amounts are difficult to perform under appropriate ceteris paribus conditions.) Generally, costs per unit final energy increase in all cases until about 2040. After 2040, costs in A1T, A1B and A1G stay more or less constant, whereas those in A1C increase further at a similar pace as before. In all A1 scenarios total global annual systems costs as percentage of GDP first increase from 5.5% in 1990 to nearly 6%, and then decline to a lower percentage level until 2100, for example, to 2.7% of GDP in the A1B baseline case in

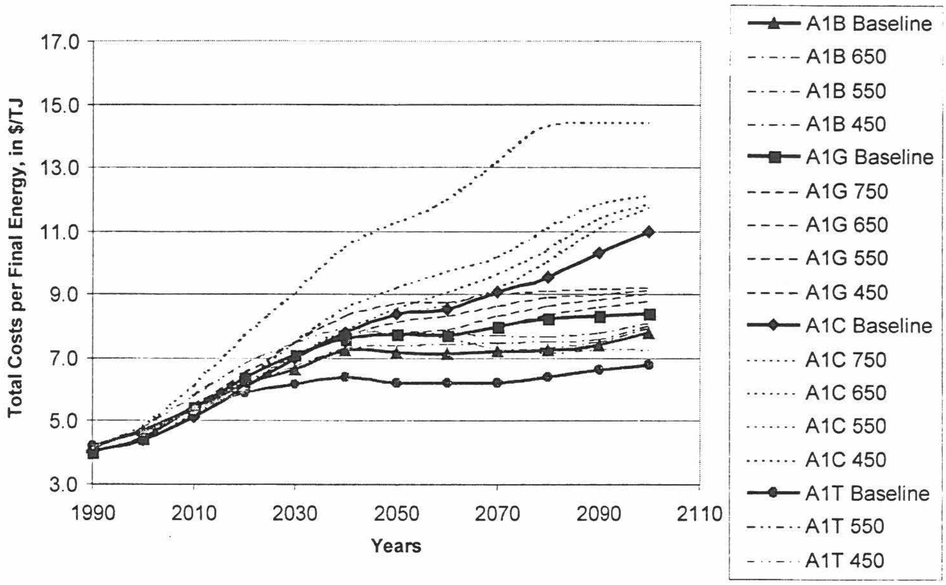

Fig. 6. Total annual (nondiscounted) system costs per final energy over time. The cost trajectories for the baselines are indicated with thick lines; those of the atmospheric CO_2 concentration stabilization cases with thin lines.

2100. Furthermore, the spread of total costs per final energy in 2100 is smaller than on average between 2040 and 2100, the reason of which lies in the dynamics of energy structural change. Consequently, this effect is highest in the rapid technological progress case A1T.

Note that MESSAGE is a technology vintage model, that is, a maximum plant life is attributed to each technology. In this terminology, CO_2 abatement costs are due to the costs of add-on technologies, the premature retiring of capital stock, and cost differences between different technologies (e.g., a coal versus nuclear power plant). The capital stock for energy production and use is typically long-lived, on the order of 30–40 years, which has important implications for investment decisions. New supply options typically take many years to enter the market. Therefore, total costs per unit energy are very similar in all A1 cases discussed here until about 2020–2030.[16]

The regional differences of CO_2 abatement costs are very large. Short- to medium-term mitigation costs are generally lower in developing and reforming economies than in today's OECD countries. This is due to the fact that developing and reforming economies today benefit from low labor costs and technological vintages that are rather inefficient. Potential efficiency gains are thus large. However, for developing countries, upfront capital investments are *the* dominant constraint, that is, global CO_2 abatement costs in the above cases are expected to be much larger if this problem of upfront investments in developing countries is not solved through measures such as technology transfer and investments from today's OECD countries.

Uncertainties about future CO_2 abatement costs (and total system costs of the baseline) are very large. Nonetheless, a number of robust analytical findings emerge

[16] An exception is the 450 ppmv CO_2 stabilization case for the coal-intensive A1C baseline, in which costly measures have to be taken from the start to achieve the stabilization goal within the given time frame.

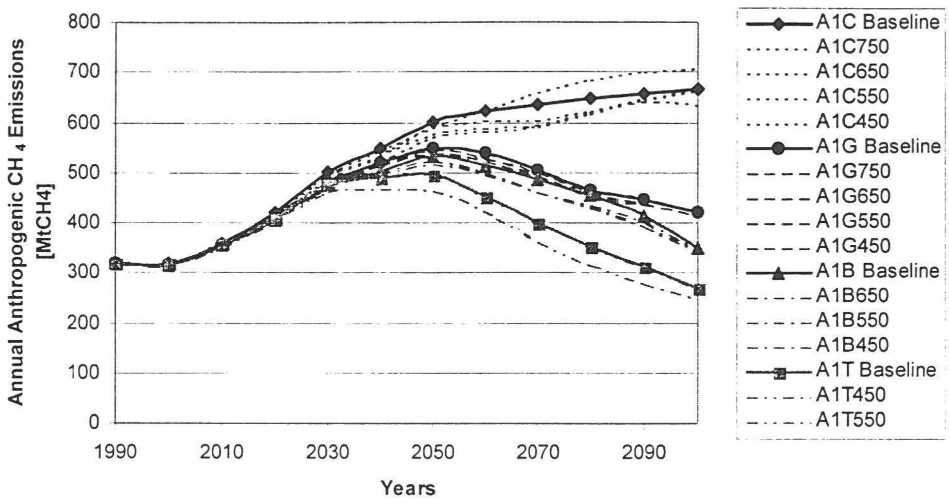

Fig. 7. Annual anthropogenic CH_4 emissions (in Mt).

from our analysis. The central result is that the variation of total system costs over the A1 baselines is larger than the variation of mitigation costs to achieve CO_2 concentration targets at alternative levels. The often seen practice of calculating an optimal tax on carbon under varying environmental constraints is heavily dependent on the rate and type of technological progress assumed for the scenario baseline. In other words, the "cost effectiveness" of alternative pathways of technological change and the measures that could induce technological change in a particular direction are as important as the cost "effectiveness" of alternative long-term environmental targets.

CONSEQUENCES OF CO_2 REDUCTION ON OTHER GHGs

Reductions of different GHGs are not independent from each other. This section gives a short summary of effects of CO_2 reduction on methane and sulfur emissions in the stabilization cases described above.

Methane Benefits of CO_2 Reduction

Figure 7 shows the reduction in global anthropogenic CH_4 emissions that are a direct consequence of CO_2 emissions reductions. Methane benefits as compared to total anthropogenic methane emissions are relatively small as the dominant methane emission source resides outside the energy sector (i.e., agricultural activities like livestock and rice paddies). However, they are considerable within the energy sector (up to about 20%). Methane benefits are highest in the A1C coal scenario because the production of coal entails large methane emissions. With structural change away from coal due to a carbon constraint, methane emissions decrease also.

Sulfur Benefits of CO_2 Reduction

Except for the coal scenario A1C baseline, absolute SO_2 emission levels in all baseline scenarios are relatively low (see Figure 8) due to technological change. Even in the A1C scenario, SO_2 emissions are much lower than in "business-as-usual scenarios" reported in the literature (for a review see [41]). This is due to two factors: First, the high income characteristics of all A1 baseline scenarios put an additional premium on local and regional air quality (and, hence, sulfur controls to combat urban air pollution

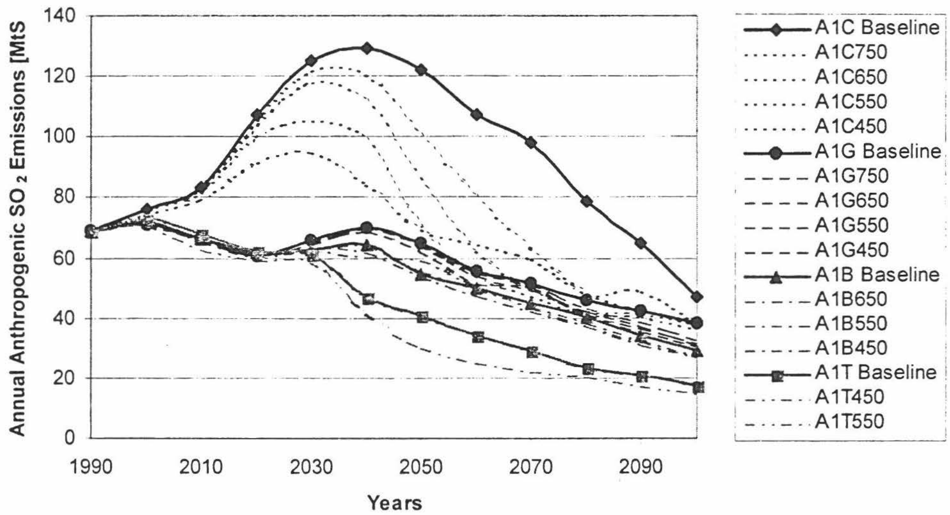

Fig. 8. Annual anthropogenic SO_2 emissions (in Mt).

and acid rain); second, the high technology dynamics assumed for all baseline scenarios that either result in continued structural change of energy systems, or the diffusion of clean technologies concerning traditional pollutants. Advanced coal technologies are thus much less sulfur emission intensive irrespective of whether the carbon externality is factured in the analysis or not. From that perspective, traditional "business-as-usual" environmental scenarios of high sulfur and carbon emissions imply extrapolating the current technological state of the art and valuation of local and regional air quality very far into the future. Sulfur benefits of CO_2 reduction are particularly high both for the rapid technological progress baseline scenario A1T and, due to the requirement of prior desulfurization when CO_2 scrubbers are used, for the high carbon control scenarios of the coal-intensive baseline scenario A1C. Just as with methane, sulfur benefits of CO_2 controls are largest in the developing countries (e.g., the coal-rich economies of Asia).

CLIMATIC IMPACTS: RADIATIVE FORCING, TEMPERATURE CHANGE, AND SEA LEVEL RISE

What are the environmental consequences of selecting one concentration or emission trajectory over another? Standard indicators of the extent of climate impacts are radiative forcing, and, consequently, global mean temperature change and possible sea level rise (see, e.g., [27] and [38, 39]).

To estimate possible climate effects of the various A1 baselines and their respective CO_2 stabilization cases, the climate model MAGICC (version 2.3) developed by Wigley [26] was used. The latest model version supports regionalized (three world regions) SO_2 emissions input data, which are important to calculate the regionally different cooling effect of sulfate aerosols. For radiative forcing we use the latest parameterizations reported in [42]. The other model input parameters for MAGGICC used here are similar to those used by the IPCC in the Second Assessment Report [27].

For all scenarios described in this article, estimations for the entire suite of direct and indirect GHG emissions were made including CO_2, CH_4, N_2O, SO_2, CFC/HFC/HCFC, PFC, SF_6, CO, VOCs and NOx. Non-energy-sector emissions were estimated

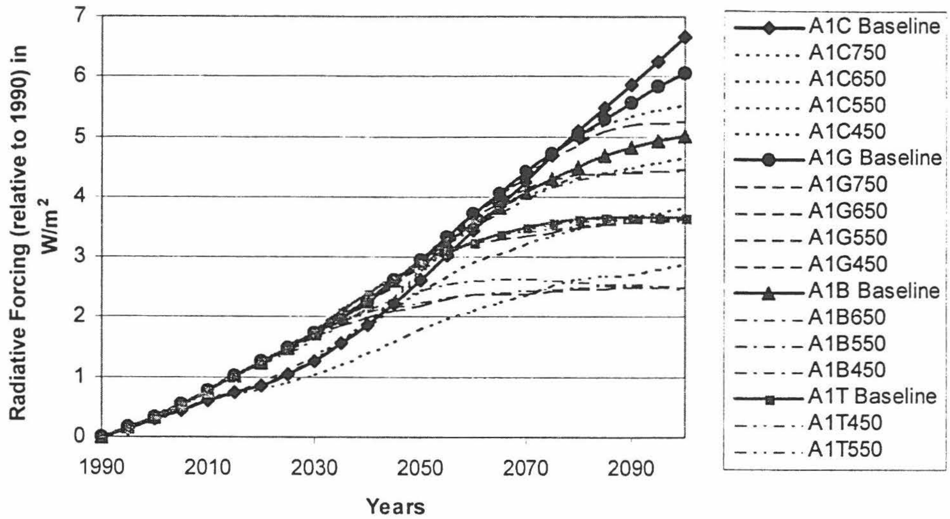

Fig. 9. Total radiative forcing due to all GHGs and SO_4 in W/m² relative to 1990.

using corresponding land use change model runs with equivalent input assumptions from the AIM model (see the contributions of Morita et al. and Riahi et al. in this issue). Halocarbon emissions are based on the scenarios developed by Fenhann (this issue). Figure 9 illustrates total radiative forcing due to all these gases relative to 1990. In the year 2100 total radiative forcing shows a large range[17] (Figure 9) from 2.5 W/m² to 6.7 W/m². Up to about the year 2040, however, total radiative forcing is nearly identical for the scenarios A1B, A1G, and A1T (Figure 9). This is due to the combined inertia of the energy system and the climate system, and a balancing effect of sulfur emissions. The more rapid the technological progress assumed for a baseline, the lower the CO_2 emissions and the lower the scenario's sulfur emissions. Decreasing sulfur emissions (Figure 8), however, enhance radiative forcing and GHG-induced *warming*, whereas decreasing CO_2 emissions decrease radiative forcing. These two effects counterbalance each other until CO_2 emissions start differing substantially among the different scenarios and SO_2 emissions have reached a very low level (from which not much further sulfur reduction is possible). In contrast to the other baselines, the coal intensive baseline A1C experiences first a doubling of SO_2 emissions until 2040 and an eventual decline (Figure 8). Until 2090 this produces a strong negative radiative forcing (or cooling) effect in A1C (summing direct and indirect effects of SO_4, see Figure 10). As a consequence, total radiative forcing for A1C until about 2040 is lower than in the other cases, although CO_2 emissions in the A1C baseline are highest of all A1 variants.

Decreasing SO_2 emissions for A1B, A1G, and A1T scenarios are a common characteristic comparable to other scenarios described in this issue (see, e.g., Riahi and Roehrl in this issue). In this respect our scenarios differ markedly from the IPCC IS92 scenario series. This difference has also important consequences on a regional level. A regional analysis of climate warming with a simple regionalized climate/ocean model (Schlesinger

[17] Total radiative forcing in the year 2100 reaches 2.5–2.9 W/m² in the 450 ppmv stabilization cases; 3.6–3.8 W/m² in A1T and the 550 ppmv stabilization cases; 4.4–4.7 W/m² in the 650 ppmv cases; 5.0 W/m² in A1B; 5.5–5.7 W/m² in the 750 ppmv cases; 6.1 W/m² in A1G; and 6.7 W/m² in A1C.

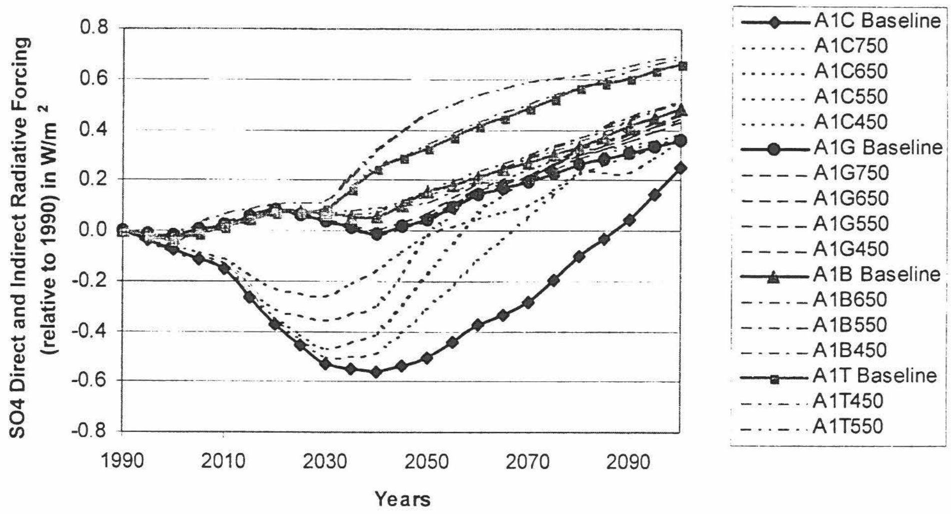

Fig. 10. Direct and indirect SO_4 radiative forcing in W/m^2 relative to 1990.

et al., in this issue) shows that reduction in regional SO_2 in A1 results in a significant warming of Europe, Asia, and North America.

Global mean temperature change (see Figure 11) shows the same pattern as radiative forcing. If we use a "best guess" climate sensitivity of 2.5°C (i.e., 2.5°C warming for a doubling of atmospheric CO_2 levels [27]), we estimate global mean temperature to change until the year 2100 by about 1.4–1.5°C in the 450 ppm CO_2 stabilization scenarios, 1.9°C in the 550 ppm stabilization scenarios, 2.2°C in the 650 ppm stabilization scenarios, and 2.6°C in the 750 ppm stabilization scenarios. However, the climate sensitivity parameter is highly uncertain. Often lower bounds for climate sensitivity parameters of 1.5°C and higher bounds of 4.5°C [27] are suggested, which would change our results

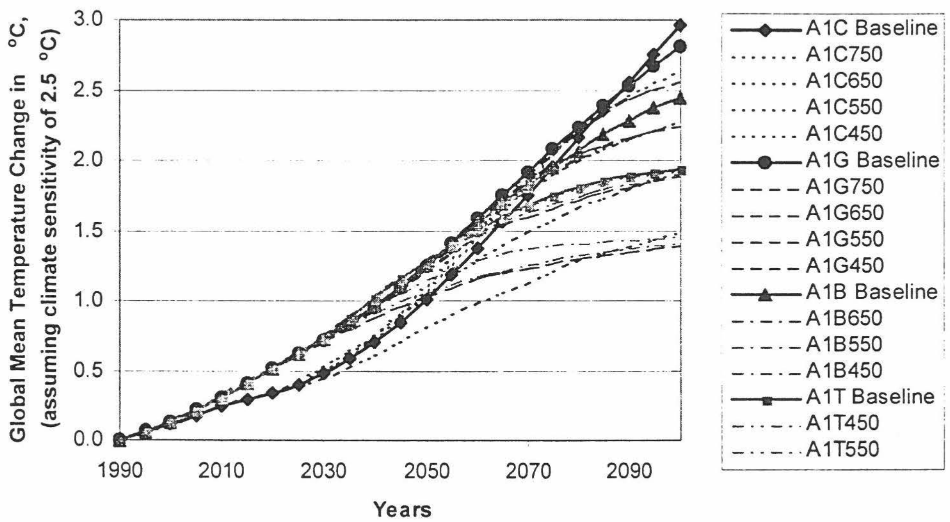

Fig. 11. Global mean temperature change in °C assuming an intermediate "best guess" climate sensitivity of 2.5°C for a doubling of CO_2 concentration.

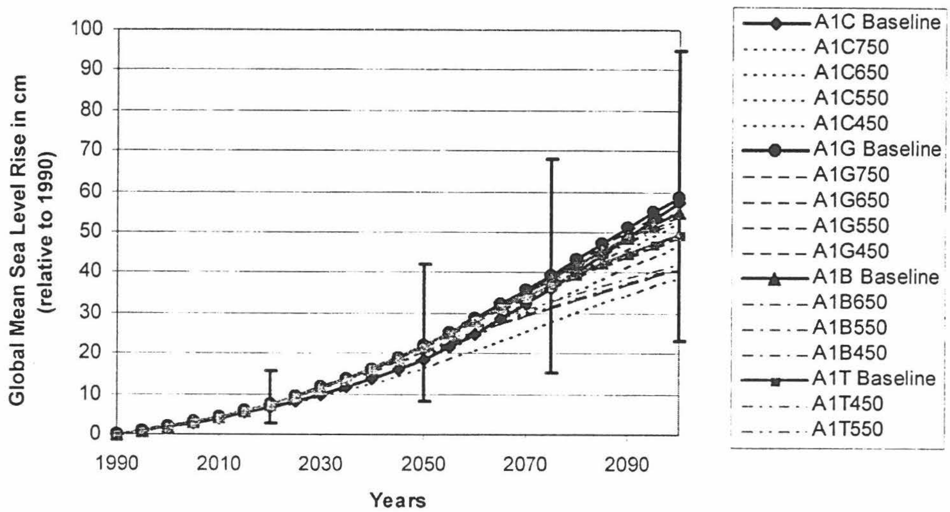

Fig. 12. Global mean sea level rise (in cm). "Best guess" trajectories using intermediate climate and sea level model parameters and GHG cycle model parameters. Uncertainty range due to low and high estimates of sea level model parameters is given for the A1B scenario.

dramatically.[18] The resulting error bar for the A1C baseline in the year 2100 is from 2.1. to 4.1°C with a "best guess" of 3.0°C; that is, this range for the A1C baseline alone is of the same order of magnitude as the range of best guesses for all the A1 scenarios combined.

Figure 12 shows "best guess" global mean sea level rise trajectories. They were calculated with the MAGGIC model using intermediate model parameterizations. Interestingly, due to the time lag between radiative forcing and sea level rise the largest sea level rise within the time frame of 1990–2100 is expected for the oil and gas-intensive A1G scenario with 59 cm in the year 2100 relative to 1990, although radiative forcing in 2100 in A1G is lower than in A1C. The lowest is the 450 ppmv CO_2 stabilization case A1C450 for the coal-intensive baseline which shows a 39 cm sea level rise by the year 2100.

Note that climate model uncertainties are very large, in particular the uncertainty of sea level rise for a particular radiative forcing. This uncertainty range (due to low and high estimates of sea level model parameters) for the A1B baseline scenario alone is 23–95 cm with a "best guess" of 55 cm in expected sea level rise in the year 2100. This is larger than the range of best guesses over *all* A1 scenarios (39–59 cm in the year 2100) (Figure 12).

Implications and Conclusion

In this article, we explored the relationship between long-term technology development in the energy sector and the possible magnitude of long-term climate change with scenarios. Embracing a dynamic perspective of technological change illustrates the sensitivity of projected future GHG emission levels to alternative developments in energy sector technologies. By exploring alternative development pathways of techno-

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[18] The ranges for A1 scenarios in this article are 1.4 to 3.0°C for a climate sensitivity of 2.5°C; 0.9 to 2.1°C for a climate sensitivity of 1.5°C; and 2.1 to 4.1°C for a climate sensitivity of 4.5°C.

logical change consistent both with historical evidence and concepts of path dependent technological change, a wide range of future GHG emissions and, hence, climate change outcomes are possible. In fact, the range of emissions that results from varying technological developments within a single scenario family (the high growth SRES A1 scenario) is as large as the range of emissions spanned by the entire range of SRES scenarios exploring the uncertainty of demographic, economic as well as environmental policy developments of the 21st century. Because of uncertainties in technological change, future GHG emissions could range from very high levels (four times larger than at present) to comparatively low levels (about the same as today), even in absence of climate policies. Therefore, we conclude that uncertainties in technological change are as important for future GHG emissions and, hence, climate change as uncertainties in long-term demographic and economic developments. This may be not be news to the readers of this journal, but it is an important conclusion for climate policy analysis which has so far devoted insufficient attention to the dynamics of technological change.

Technological change is also a paramount determinant of future energy costs, for lowering future costs of complying with climate control targets, and for the realization of synergies between various GHG emission reduction measures. Embracing a cost benefit framework for climate change policy analysis means we have to consider the inherent uncertainties in cost differences of underlying baseline scenarios. We have shown that these baseline cost differences are larger than the cost differences of meeting alternative climate stabilization targets. This leads to two important methodological and policy conclusions. First, improved future models should treat technologies and technological change as uncertain, should include initial upfront R&D costs of new technologies in the cost analysis, and finally should include estimates of end-use sector investments. Second, considering the long-term nature of the climate change problem and its inherent uncertainties (precise targets cannot be established at present), climate policies perhaps need to be extended to include *technology policy*.

According to our calculations, a coal-based synthetic fuel economy scenario has both the highest overall energy systems costs as well as the highest costs of complying with climate policy targets, which illustrates the need to avoid a premature "lock-in" in such a pathway of long-term technological change. Scenarios of accelerated technological change might require long-term RD&D commitment in new energy technologies, upfront investments and accumulation of experience in niche markets. This requires both long-term perspectives as well as long-term policy orientations rather than a focus on short-term emission reduction targets. Preferences between scenario alternatives will be also based on other factors, for example, the relative desirability or undesirability of the large materials handling requirements of massive CO_2 sequestration and its possible environmental impacts in case of a coal-intensive scenario, preferences between "upstream" and "downstream" RD&D, the acceptability of alternatives such as nuclear power, and the relative priority given by different nations to energy security.

An important finding from our scenario exercise is that even in scenarios of path-dependent technological change favoring fossil fuels, the long-term technology portfolio needs to include improvements in nuclear, renewables, and gas-related technologies and infrastructures. Innovative "transitional" strategies of using natural gas as a "bridge" toward a carbon-free hydrogen economy (including CO_2 sequestration) are also at a premium in a possible carbon constrained future world. These are obvious priority candidates for enhanced RD&D efforts, with particular emphasis on their applicability for developing countries, the dominant source of energy-related CO_2 emissions in the long term. Such a technology policy response appears especially meaningful for applying the precautionary principle under persistent and large uncertainties with respect to timing and magnitude of climate change and its impacts.

Yet, the valuation of local and regional environmental quality in an affluent world is likely to lead to accelerated control of sulfur emissions, which could amplify possible climate change. Important tradeoffs are therefore likely to persist for environmental policy throughout the 21st century. Accelerated technological change can widen the response portfolio in the face of multiple long-term contingencies. But tough decisions need to be addressed: whether to focus on short-term local and regional environmental issues or on long-term climate change, such as focusing resources on meeting short-term carbon limits as exemplified by the Kyoto Protocol versus expanding response options for meeting (perhaps tougher) long-term targets through accelerated technological change. Informing policymakers about the importance and inherent uncertainties of technological change as well as improving its treatment in models and scenario studies remain important objectives for the analytical community. For society at large it means understanding (and accepting) that we need more technology and not less in responding to long-term environmental challenges.

Appendix: A1 "Storyline"—A Narrative Description

The *A1 storyline* is a short narrative description of the main characteristics of the A1 scenario family developed by the international team featured in this issue.[19] It serves as a main background document for the scenario quantifications using formal models reported in this article and is reproduced in abridged form here:

> The A1 storyline is a case of rapid and successful economic development, in which regional averages of income per capita converge: current distinctions between "poor" and "rich" countries eventually dissolve. The primary dynamics are a strong commitment to market-based solutions; high savings and commitment to education at the household level; high rates of investment and innovation in education, technology, and institutions at the national and international level; and international mobility of people, ideas, and technology. The transition to economic convergence results from advances in transport and communication technology, shifts in national policies on immigration and education, and international cooperation in the development of national and international institutions that enhance productivity growth, technology innovation, and diffusion.
>
> In the A1 scenario family, demographic and economic trends are closely linked, as affluence is correlated with long life and small families (low mortality and low fertility). Global population grows to some nine billion by 2050 and declines to about seven billion by 2100. Average age increases, with the needs of retired people met mainly through their accumulated savings in private pension systems.
>
> The global economy expands at an average annual rate of about 3% to 2100. This is approximately the same as average global growth since 1850, although the conditions that lead to this global economic growth in productivity and per capita incomes in the scenario are unparalleled in history. Global income per capita reaches about US$21,000 by 2050. While the high average level of income per capita contributes to a great improvement in the overall health and social conditions of the majority of people, this world is not necessarily devoid of problems. In particular, many communities could face some of the problems of social exclusion encountered by the wealthiest countries in the 20th century, and in many places income growth could come with increased pressure on the global commons.
>
> Energy and mineral resources are abundant in this scenario family because of rapid technical progress, which both reduce the resources needed to produce a given level of output and increases the economically recoverable reserves. Final energy intensity (energy use per unit of GDP) decreases at an average annual rate of 1.3%.

[19] The original version of the A1 storyline was created by Arnulf Grübler, a member of the abovementioned international team.

The A1 marker scenario is based on a balanced mix of primary energy sources and has an intermediate level of CO_2 emissions, but depending on the energy sources developed, emissions in the A1 scenario variants cover a very wide range. In the fossil-fuel-intensive variants, emissions approach those of the A2 scenarios of the SRES scenario set; conversely, in variants with low labor productivity or of rapid progress in "post-fossil" energy technologies, emissions are intermediate between those of the B1 and B2 scenarios (see Bert de Vries et al., and Riahi and Roehrl, in this issue).

Ecological resilience is assumed to be high. Environmental amenities are valued and rapid technological progress "frees" natural resources currently devoted to provision of human needs for other purposes. The concept of environmental quality changes in this storyline from current emphasis on "conservation" of nature to active "management" of natural and environmental services.

With the rapid increase in income, dietary patterns shift initially toward increased consumption of meat and dairy products, but may decrease subsequently with increasing emphasis on health of an aging society. High incomes also translate into high car ownership, sprawling suburbanization, and dense transport networks, nationally and internationally.

A1 Variants: Several variant scenarios have been considered in the A1 scenario family that reflect the uncertainty in development of energy sources and conversion technologies in this rapidly changing world. Some of the variants evolve along the carbon-intensive energy path consistent with the current development strategy of countries with abundant domestic coal resources. Other variants intensify the dependence on oil, and in the longer run, natural-gas resources. The third group envisages a stronger shift toward renewable energy sources and, conceivably, also nuclear energy. The implications of these alternative development paths for future GHG emissions are challenging: The emissions vary from the carbon-intensive to decarbonization paths by at least as much as across the variation of all other driving forces across the other three scenario families.

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