THE CONSISTENCY OF IPCC'S SRES SCENARIOS TO RECENT LITERATURE AND RECENT PROJECTIONS

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Abstract. The greenhouse gas emissions scenarios published by the IPCC in the *Special Report on Emission Scenarios* (SRES) continue to serve as a primary basis for assessing future climate change and possible response strategies. These scenarios were developed between 1996 and 1999 and sufficient time has now passed to make it worth examining their consistency with more recent data and projections. The comparison performed in this paper includes population, GDP, energy use, and emissions of CO_2, non-CO_2 gases and sulfur. We find the SRES scenarios to be largely consistent with historical data for the 1990–2000 period and with recent projections. Exceptions to this general observation include (1) in the long-term, relatively high population growth assumptions in some regions, particularly in the A2 scenario; (2) in the medium-term, relatively high economic growth assumptions in the LAM (Latin America, Africa and Middle East) region in the A1 scenario; (3) in the short-term, CO_2 emissions projections in A1 that are somewhat higher than the range of current scenarios; and (4) substantially higher sulfur emissions in some scenarios than in historical data and recent projections. In conclusion, given the relatively small inconsistencies for use as global scenarios there seems to be no immediate need for a large-scale IPCC-led update of the SRES scenarios that is solely based on the SRES scenario performance vis-a-vis data for the 1990–2000 period and/or more recent projections. Based on reported findings, individual research teams could make, and in some cases already have made, useful updates of the scenarios.

1. Introduction

In 2000 IPCC published a new set of emission scenarios in the *Special Report on Emission Scenarios (SRES),* designed to serve as a basis for assessments of climate change and possible response strategies (Nakicenovic, 2000). The SRES scenarios were developed in a relatively open process that started in 1996. Six modelling teams officially participated in the exercise to develop new scenarios.[1]

The IPCC scenarios cover very long time periods (1990–2100) so as to capture the large inertia involved in the climate system and the long time scales involved in fundamental changes to energy systems. Uncertainties obviously play a major role over such a long time period. Future greenhouse gas emissions result from complex dynamic processes, including demographic and socio-economic development, and technological change. The future evolution of these factors is highly uncertain, with various development patterns capable of introducing very different futures. The SRES process addressed uncertainty in two ways. First, the scenarios were based on

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a set of storylines describing alternative broad development patterns. Each storyline was intended to represent consistent demographic, social, economic, technological, and environmental developments. Second, in order to capture uncertainties related to model structure, the SRES process included six different models for creating quantitative interpretations of each of the storylines.

The IPCC SRES scenarios have been used extensively since their publication, and a considerable amount of this work was evaluated in IPCC's Third Assessment Report (Houghton et al., 2001; McCathy et al., 2001; Metz et al., 2001). This included research into possible climatic change, impact and adaptation studies, and analysis of potential mitigation policies. The SRES scenarios will also serve as the basis for many of the impact studies to be assessed in the IPCC Fourth Assessment Report now underway. The SRES scenarios have also served as a basis or inspiration for numerous other exercises at global, regional and national levels – where often new modelling was consistent with the overall SRES storylines and published parameters (UNEP, 2002; De Mooij and Tang, 2003; Kainuma et al., 2003; Van Vuuren et al., 2003).

At the same time, several criticisms of the SRES scenarios have been made, mainly outside of the peer-reviewed literature. These are mostly concerned with economic growth assumptions of some of the scenarios (growth considered too high), but also include the argument that SRES researchers have ignored some of the historical trends in the drivers used to develop the emission scenarios (Castles and Henderson, 2003). A claim was also made that the IPCC scenarios were already off track with respect to historical emission trends (e.g. Corcoran, 2002). Independent of the validity of these specific criticisms, it is clear that scenarios do not have an unlimited lifetime. The information on which they are based can become outdated, actual events can proceed in ways substantially different than foreseen in the scenarios, and/or the specific questions for which the scenarios were developed can change (e.g. emphasis can shift toward identifying policy options, and away from exploring the consequences of inaction). In fact, there are numerous examples of scenarios that have not stood the test of time, including energy forecasts made before and during major events such as the oil price spikes of the 1970s and early 1980s (Smil, 2000; O'Neill and Desai, 2004). Past population scenarios have also sometimes become quickly outdated, as fertility or mortality trends have shown quick and sharp divergence from anticipated directions (O'Neill et al., 2001).

Although the SRES scenarios were published in 2000, most models used to develop the scenarios were calibrated on 1990 and 1995 data, and most of the calculations were done well before 1999 (when the review process started). New information is now available that can be compared against the SRES scenarios. First, new historic data for the 1990–2000 period can be compared against SRES assumptions for this time period. Second, new projections can be compared to the SRES outlook. These new projections can be expected to include the latest data, knowledge and insights into events that have occurred since the development of SRES and that could affect future trends. Such outlooks often focus on shorter time frames than SRES (20–30 years instead of 100 years). In some cases, however, new long-term scenarios have been published.

In this paper, we examine the consistency of the IPCC SRES scenarios with available 1990–2000 data and recent projections. We also consider the implications of these comparisons for the credibility and validity of the scenarios – and consequently for the desirability of using SRES in further assessment. It should be noted that from the perspective of comprehensive assessments of the climate change issue, such as those carried out by IPCC, there are good reasons to prefer the use of a given set of emission scenarios for a sufficiently long time period to allow their use in assessments of potential future climate change, its impacts, and the costs and benefits of climate policies. Thus minor inconsistencies between the scenarios and recent trends are unlikely to outweigh the benefits of a consistent basis for different types of assessment studies.

Section 2 discusses several methodological issues, followed by the results of the comparison for a set of driving forces (population, economic growth and energy use) in Section 3 and emissions in Section 4. Conclusions are presented in Section 5.

2. Methodology

We focus our assessment on the SRES scenarios as published by IPCC (Nakicenovic, 2000).[2] Box 1 discusses some of the terminology used in SRES scenarios and its relevance to this exercise. In our analysis, we focus on the so-called marker scenarios since they have been the most often used in different applications, including the IPCC Third Assessment Report. These markers were also references for the alternative elaborations of each scenario by other modelling groups. Where possible, we have added ranges associated with the alternative elaborations of each storyline as uncertainty ranges around the IPCC marker scenarios.

From the total set of data published by SRES, we selected a set of the most crucial variables for our comparison, i.e. GDP, population, energy use and emissions of CO_2, other greenhouse gases and sulfur. Comparison is performed at the level of aggregation reported by SRES, i.e. four geographical regions 1) OECD-1990, 2) Reforming Economies (Central and Eastern Europe and Former Soviet Union, REF), 3) Asia and 4) Africa, Latin America and Middle East (ALM).[3] Three types of comparisons are made: 1) to data covering the (by now) historical 1990–2000 period, 2) to short-term projections published since 2000 and 3) to long-term projections published since 2000. The projections used in our comparison have been selected based on their recent publication dates and the fact that they are often used as reference projections within their specific domains. In addition, we exclude projections that assume climate policies. Since all SRES scenarios exclude climate policy (based on the aim to explore events in the absence of such policies), comparisons with intervention scenarios would not be meaningful.

Marker scenarios

In total, the SRES report discusses six scenario storylines, grouped into four scenario families. The assumptions of these families differ in two fundamental ways (two axes): 1) emphasis on ongoing globalization versus regional identity (these scenarios are marked as '1', respectively '2' scenarios) and 2) the emphasis on economic development versus social and environmental factors (these scenarios are marked as 'A', respectively 'B' scenarios). Combining these axes results in the four scenario families, named after underlying fundamental assumptions: A1, A2, B1 and B2. In addition, two other scenario storylines (termed 'illustrative scenarios') result from different technology assumptions within the A1 family. For each storyline, several quantitative scenarios exist, produced by different modelling groups (40 in total). Four of them were designated as 'marker' scenarios by the SRES writing team, as they were considered to be illustrative of a particular storyline. These marker scenarios are by far the most often used (and have also served partly as a guiding light for the other scenarios within the family). Our comparison focuses on these marker scenarios.

Standardization of base-year data (emissions only)

For the 1990-2000 period, the emission data from the SRES scenarios have been subject to a process of 'base-year data standardization'. This was done because the underlying data of the different models showed notable differences for base-year emissions, mostly reflective of scientific uncertainty in emissions data, but also of differences in model calibration and model base year. In order to improve scenario comparability, a decision was made to adopt standardized numerical values for reported greenhouse gas emissions for the 1990 base year and for 2000. These standardized values were derived by taking the average of the different models for those years. Since the purpose of this exercise is to evaluate the SRES scenarios as they are published, and normally used (and not to evaluate the performance of the underlying models), we have compared these numbers to current data inventories for the same period. This means that only 1 set of (SRES) emissions data for 1990 and 2000 needs to be compared against historical data. In contrast, the data for driving forces have not been standardized and thus individual model results and assumptions can be compared against historical trends.

Based on (Nakicenovic, 2000)

Box 1. Terminology from the IPCC SRES scenarios.

In theory, a fourth comparison could include comparing historic trends to (short-term) trends in the SRES scenarios. However, we consider this kind of comparison outside the scope of our current analysis, which focuses on new information since the publication of SRES. Moreover, the SRES scenarios in fact deliberately assume that trends in driving forces in the future could be substantially different than the past (hence the storylines). However, since short-term projections often rely substantially on past trends, our comparison implicitly accounts for these trends to some degree. In one case (sulfur emissions) we also explicitly note that SRES outcomes break with 1990–2000 trends.

The most important comparisons have been made with the projections of the International Energy Agency's World Energy Outlook (IEA, 2002; IEA, 2004) and US Department of Energy's International Energy Outlook (US.DoE, 2003) (which both report on GDP, energy use and CO_2 emissions), and the results of the model comparison study done by the Energy Modelling Forum (EMF-21) (Weyant et al., 2005). From the last study, we used the so-called 'modeller's reference scenario' which are usually 'medium-growth' scenarios. In total, available data from this study included long-term data for 11 models, 3 of which were also included in SRES. Given the fact that these three models have been further updated, and do not dominate the results of the total EMF-study, the EMF study can safely be used as an independent source of information from SRES. In addition, for population we used projections from the UN Population Division (UN, 2003), IIASA (IIASA, 2001; Lutz et al., 2004) and the U.S. Census Bureau (US.BoC, 2003). For GDP, we used the global economic prospects of the World Bank/GEF (WorldBank, 2004), and for emissions data we use selected modelling studies. It should be noted that the historical data can have considerable levels of uncertainty attached to them. Where possible, we commented on the degree of certainty attached to the specific data sources. It should also be noted that several recent scenario studies such as UNEP's Global Environment Outlook (UNEP, 2002) have not been selected because they are, at least partly, based on the IPCC scenarios and therefore cannot be regarded as sufficiently independent.

In the remainder of this section, we cover two more methodological issues: 1) the assumptions underlying the SRES scenarios, and 2) the relevance of comparing SRES scenarios to short-term projections (and derived criteria for comparison).

2.1. ASSUMPTIONS UNDERLYING THE IPCC SCENARIOS

The main assumptions underlying the four scenario families (A1, A2, B1 and B2) are indicated in Table I. The scenarios are defined along two main axes (globalization versus regionalization, and economic orientation versus orientation to social development and environmental protection), but differ in many other ways too. The total set is considered to represent a wide range of outcomes. At the same time,

TABLE I
Main storyline assumptions underlying the SRES scenarios

	A1			A2	B1	B2
Storyline	Globalization; liberalization;			Heterogeneous world; self-reliance; fragmentation	Globalization; orientation on social and environmental sustainability	Local solutions to sustainability; regional emphasis
Population	Low			High	Low	Medium
Economic growth	Very high			Low in developing countries; medium in industrialized countries	High	Medium
Primary energy use	Very high			High	Low	Medium
Technology development	Rapid			Slow	Rapid	Medium
Type of technology development	Balanced (A1B)	Primarily fossil fuels (A1FI)	Primarily non-fossil energy (A1T)	Balanced	Primarily energy efficiency and non-fossil energy	Balanced

this does not mean that the four families represent all possible outcomes or a representative sample across the possible outcomes. In fact, based on the information available at the time that the SRES scenarios were developed, the assumed trends for drivers include (see also Table I):

– more high to very high economic growth scenarios (A1 and B1) than low economic growth scenarios (A2),
– more high to very high energy use scenarios (A1 and A2) than low energy use scenarios (B1) and
– more low population scenarios (A1-B1) than high population scenarios (A2).

2.2. THE RELEVANCE OF COMPARING SRES SCENARIOS TO RECENT PROJECTIONS

There are two important aspects in which the SRES scenarios differ from some of the other types of projections in the literature: (1) SRES scenarios explore alternative possible futures rather than attempting to identify a single most likely outcome, and (2) the SRES scenarios have a very long time horizon. These differences raise questions about the relevance of comparisons between SRES and other projections.

When comparing the SRES scenarios to 'best-guess' studies, differences between best-guess projections and SRES scenarios do not necessarily indicate important inconsistencies. By definition, the SRES scenarios are intended to capture a wide range of possible outcomes. At the same time, a comparison of the SRES range with current best guess projections can give a sense of the relative bias of the SRES scenarios with respect to the current outlook. For example, in an extreme case, if all SRES scenarios occurred below the current best guess outlook for a particular variable, we could conclude that SRES was biased substantially to the low side of the current outlook. This would not necessarily mean that the SRES scenarios were implausible (because best guess projections in themselves give no indication of the range of plausible outcomes). However, it would indicate that SRES did not cover the full range of plausible outcomes (and in this extreme case would not even include the outcome considered most likely).

When comparing SRES scenarios to short-term studies that include a range of possible outcomes, attention must be paid to what this range is intended to represent. For example, interpreting the results of the comparison for its implications for the validity of the SRES scenarios is difficult if the range simply represents the result of a sensitivity analysis, but includes no characterization by the authors of the likelihood of the outcome. The UN population projections are one such example; they include a most likely "medium" scenario as well as high and low variants demonstrating the sensitivity of outcomes to assumptions on future fertility rates (UN, 2003). Similarly, the EIA global energy projections include a single best-guess outcome, and high and low scenarios that reflect sensitivity to assumptions regarding GDP growth (US.DoE, 2004a). In such cases, if some SRES scenarios fall outside alternative high and low projections, it does not necessarily imply that the SRES results are unlikely. Indeed, there is evidence from the examination of errors in past projections that it is not uncommon for actual developments to quickly exceed the low or high bounds of such projections, even over relatively short time horizons (e.g., Shlyakhter et al., 1994).

One can only conclude that the SRES scenarios are unlikely if the high and low projections to which they are compared are associated with some judgment of likelihood. Probabilistic projections for population (Lutz et al., 2001) and CO_2 emissions (Webster et al., 2002; O'Neill, 2004) exist and can be used in this way, although it must be kept in mind that the probability distributions involved in these examples are subjective.

Regarding the issue of the different time horizons of various projections, it is important to keep in mind potential methodological differences in developing longer- vs. shorter-term outlooks. The modelling tools used in SRES focus primarily on long-term processes such as capital turnover, technological progress, resource depletion and substitution. In contrast, analysis concentrated on the short term (i.e. 10–20 years) generally demands different tools and scenarios that take specific national policies and circumstances more directly into account. Still, one might reasonably expect the SRES scenarios to describe the transitions from the present to the long-term underlying logic with some degree of plausibility, at least at an aggregate level. In this context, there are (at least) three valid arguments why consistency between long-term scenarios (like SRES) and short-term historical trends and outlooks is relevant:

1. If inconsistency with historical trajectories and/or near-term expectations is large enough, it could render part (or all) of the long-term scenario logic, driving force assumptions or scenario results unlikely or even implausible.
2. The medium term (e.g. around 2025) can be a crucial period in mitigation and adaptation analysis – even if studies cover a much longer time frame.

Long-term scenarios, like SRES, are often used as baselines in such studies. Moreover, while SRES is not intended to capture short term uncertainty, if short term trends in SRES are implausible then it is important information for potential users.

3. An insufficient match between SRES and short-term trends or historical data can undermine credibility of the scenarios, whether or not such a match is meaningful in substantive terms.

The relevance of these arguments clearly depends on the type of application (the two extremes being formed by climate modelling versus mitigation analysis). In mitigation analysis, required measures and costs in the first few decades tend to be crucial for overall results. This implies that for mitigation analysis, all of the above arguments are relevant. In contrast, given the long-term focus of climate modelling (a hundred-year time frame or more), only the first and third arguments apply. It should also be noted that because climate modelling generally requires large resources and time, the turnover rate of scenarios needs to be much slower as well. The use of SRES in impact assessment occupies an intermediate position, both in terms of the appropriate turnover rate of scenarios and the outlook period for this type of assessment. Given the fact that SRES scenarios are used for a wide-range of applications, we have decided to focus on a *reasonable* match between the SRES scenarios and new information on historical data, short-term outlooks or long-term scenarios. Our judgments on reasonableness take into account that (a) a good performance on trends is more essential that an exact reproduction of specific results for any given year, and (b) historical data also have some uncertainty, so that "matching" such data is to some extent a statistical concept.

3. Results for Main Driving Forces

3.1. POPULATION

3.1.1. *Historical Trends*

The SRES emissions scenarios use three population projections produced in 1996 by the UN (UN, 1998, for the B2 scenario) and the International Institute for Applied Systems Analysis (IIASA) (Lutz et al., 1996, for the A1/B1 and A2 scenarios). Both of these projections had a base year of 1990. As shown in Table II, the SRES population values for 1990 and 2000 are quite close to the most recent estimates of population size for the world and the four SRES macro regions. Some differences are to be expected since historical population estimates undergo constant revision. In particular, the most recent population estimates have the benefit of drawing on data from the censuses held around the year 2000 in many countries of the world, but not available at the time the projections used in SRES were produced. While revisions to population totals for particular countries can be substantial, at

TABLE II
Comparison of SRES population trends with 1990–2000 data (in millions)

		UN data	A1/B1	A2	B2
1990	OECD	866	864	864	863
	REF	412	412	412	412
	Asia	2791	2807	2807	2788
	ALM	1195	1200	1200	1188
	World	5264	5282	5282	5251
2000	OECD	929	919	923	916
	REF	411	419	421	415
	Asia	3246	3260	3295	3248
	ALM	1485	1519	1530	1510
	World	6071	6117	6171	6089
Ratio 2000/1990	OECD	1.07	1.06	1.07	1.06
	REF	1.00	1.02	1.02	1.01
	Asia	1.16	1.16	1.17	1.16
	ALM	1.24	1.27	1.28	1.27
	World	1.15	1.16	1.17	1.16

Source. UN, 2005.

larger levels of aggregation they are generally small. This is reflected in the close agreement between the updated estimates and the SRES values.

A second reason that the SRES values are relatively close to recent estimates for the year 2000 is that short term projections (for example, from 1990 to 2000) have a relatively small uncertainty (particularly for large world regions) due to the large influence of demographic inertia (momentum) on short term population trends. Given a particular base-year population in 1990, much of the population change over the next decade is already built in to the existing age structure. Partly for this reason, the current estimate of a global population size of 6.07 billion in 2000 is not much different from the SRES figures of 6.09–6.17 billion. While differences are larger at the world region level, in no case are they large enough to question the credibility of the SRES scenarios on the basis of historical trends in population size.

3.1.2. *Recent Projections for the Medium Term*

The population projections used in SRES were consistent with the demographic outlook at that time (Gaffin, 1998). The projection used in the B2 scenarios was the UN medium variant (UN, 1998). The A1 and B1 scenarios all shared a common, relatively low, population projection from IIASA, while the A2 scenario used a relatively high population projection from IIASA (Lutz et al., 1996). These two projections spanned, at the global level, approximately the 90% uncertainty interval associated with the IIASA probabilistic projections (i.e. a level just within the 5th and 95th percentiles of the distribution).

Updated projections, however, generally anticipate less global population growth than the projections used in the SRES scenarios. Since the early 1990s, birthrates in many parts of the world have fallen surprisingly fast and the AIDS epidemic has taken an unexpectedly large toll. These changes have led demographers to revise their outlook on future population size downward, toward smaller, older populations than previously anticipated. For example, Figure 1a compares the projections for 2050 used in SRES to the most recent IIASA (Lutz et al., 2001, 2004), UN (2005), World Bank (2005) and the US Census Bureau (US.BoC, 2005) projections for the world and the four SRES macro regions. For comparability, the figure plots all population sizes relative to the projected population in the SRES B2 scenario for each region (i.e. the UN medium scenario produced in 1996).

For the world as a whole, population was projected at 9.4 billion in 2050 in the SRES B2 scenario. Figure 1a shows that the A2 scenario anticipated a 21% larger global population, and the A1 and B1 scenarios, a 7% smaller population than the B2 scenario. When these scenarios are compared to more recent projections for the world, a small downward revision to the medium (or "best guess") projections and to the high end of the uncertainty range is shown, along with a relatively large downward revision to the low end of the uncertainty range. As a group, updated medium projections foresee a 3–10% (0.3 to 0.9 billion) smaller global population in 2050 relative to the SRES B2 projection. Similarly, the high end of the range has shifted down, so that the SRES A2 scenario now no longer falls within the 90% uncertainty interval; it now falls 6–7 percentage points (0.5–0.7 billion people) above the updated UN high scenario and the 95th percentile of the IIASA uncertainty range. At the low end of the range changes are much larger: the SRES A1/B1 assumptions fall 11–18 percentage points (1.0–1.7 billion people) above the UN low scenario and the 5th percentile of the IIASA uncertainty range.

Considering the four SRES macro regions, Asia and ALM drive the global results due to their very large absolute sizes. Analysis of smaller sub-regions (not shown) indicates that changes are primarily due to changes in the outlook for Sub-Saharan Africa, the Middle East and North Africa region, and the East Asia region, particularly China. Recent data showing lower than expected fertility in these regions has led to less projected population growth. In addition, a much more pessimistic view on the extent and duration of the HIV/AIDS crisis in sub-Saharan Africa has also lowered anticipated growth in that region.

Changes in the outlook in the industrialized countries differ substantially from the global pattern. In the OECD region, the UN projections are actually about 12% *higher* than previously, despite continuing low fertility in these regions, due mainly to changes in assumptions regarding migration. Previous UN projections did not attempt to project migration beyond 2025, assuming instead that it was zero afterwards; the updated projections assume non-zero migration through 2050. Updated IIASA projections are also slightly higher in this region, due mainly to a

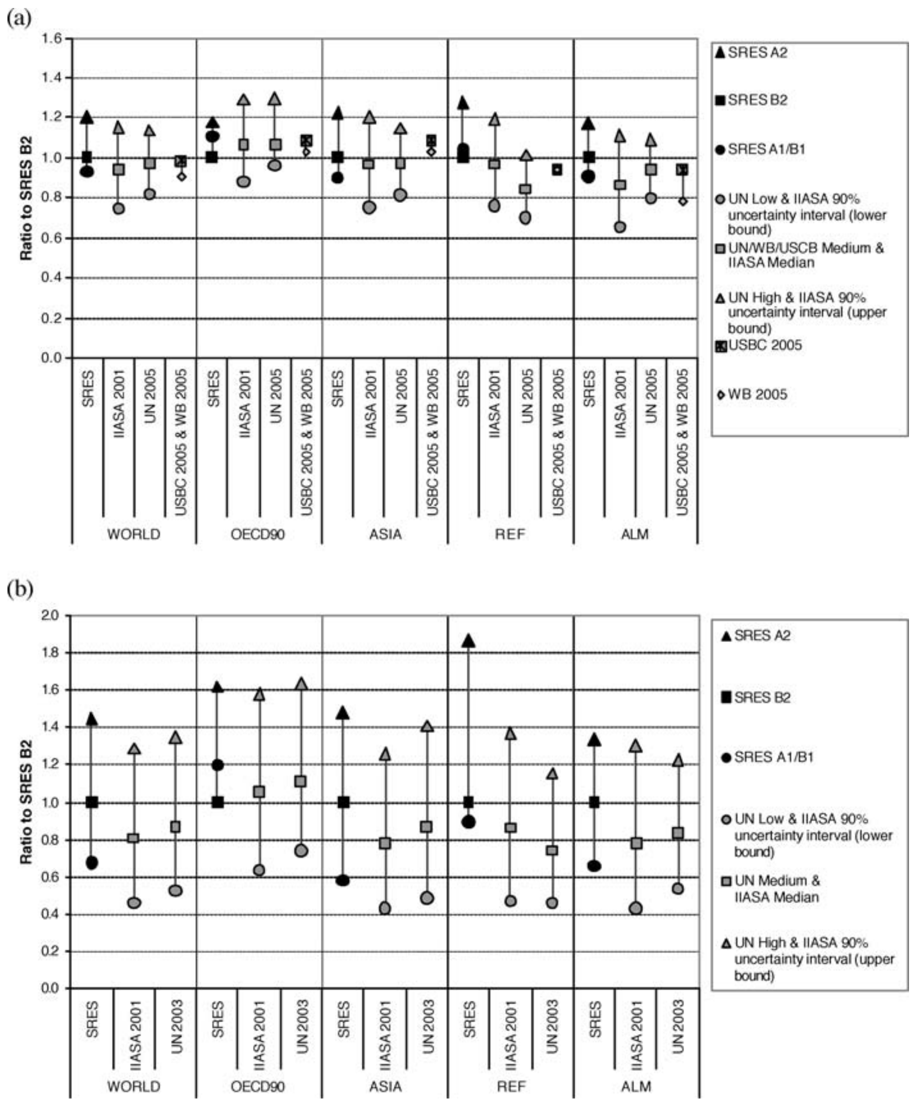

Figure 1. Population size worldwide and for four SRES macro regions, relative to the population size in the SRES B2 projection for (a) 2050 and (b) 2100. Source: (Nakicenovic, 2000; Lutz et al., 2001; UN, 2005; US.BoC, 2005; WorldBank, 2005).

more optimistic projection of future life expectancy. In the REF region, projections from both institutions have been revised downward, especially in the UN projections and for the high end of the uncertainty range. These changes have been driven by recent data showing very low fertility levels and mortality that is quite high relative to other industrialized countries, particularly in the Former Soviet Union.

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

3.1.3. *Recent Projections for the Long Term*

Because population growth is a path-dependent process, changes in the estimates for the base year and in the short-term outlook can have important implications for the plausibility of long-term population growth paths. Therefore it is worth comparing the SRES population assumptions to updated projections for the end of the century. Among the major institutions that regularly produce population projections, IIASA and the UN are the only ones that have produced updated projections for the world that extend to 2100, shown in comparison to the SRES assumptions in Figure 1b. Patterns are qualitatively similar to those found for 2050, but larger in magnitude: a general downward shift in the full range of projections that is somewhat larger at the lower end. For example, the most recent central projections for global population are 13–19% (1.4–2.0 billion people) lower than the medium population scenario used in the SRES B2 scenarios. Similarly, the SRES A2 population assumption of 15 billion in 2100 is now 10–16 percentage points (1.1–1.7 billion) above the UN high and IIASA 95th percentile. At the low end differences are larger: the UN low and IIASA 5th percentile are 15–22 percentage points (1.6–2.2 billion) below the SRES A1/B1 assumptions.

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

3.1.4. *Credibility of SRES Assumptions*

Although the range of projected population sizes has shifted down since the development of the SRES scenarios, this does not automatically imply that the SRES population assumptions are no longer credible. For example, the assumptions used in the SRES B2 and A1/B1 scenarios still fall within the plausible range of population outcomes according to more recent outlooks (see Figure 1). What is clearly missing, however, in the current SRES set is a population projection that is representative of the lowest end of the current range of projections. This implies that if new scenarios were to be developed today it would make sense to choose lower population growth assumptions, and for this reason some researchers have produced revised versions of the SRES population assumptions. For example Hilderink (Hilderink, 2004) provides an alternative interpretation of the demographic implications of the SRES storylines, and produces four new global population projections that span a range of 8 to 12 billion in 2100 (as compared to 7 to 15 billion in SRES).

At the high end of the range, the comparison of SRES to the updated outlook is less favorable. The population projection used in the A2 scenarios now falls above the 95th percentile in the IIASA projections and above the most recent UN high scenario. Differences are especially large in particular regions such as East Asia, Middle East, North Africa and the Former Soviet Union. In these regions, the SRES assumptions now strain credibility, a fact that should be taken into account by scenario users. It is advisable to use revised projections for the regions with the largest differences if possible. For example, IIASA has recently produced a new population scenario for use in a stabilization variant of an A2 storyline that results in a population of about 12 billion in 2100.

It should also be kept in mind that while in the few regions discussed above there is a clear inconsistency between the SRES A2 population assumptions and the more recent outlook, there is, in general, a substantial range of population outcomes that is consistent with any given SRES storyline (O'Neill, 2004). As long as there is consistency between the population assumptions used to generate emissions and to evaluate impacts, researchers need not feel tightly bound to a single population projection for each storyline.

3.2. ECONOMIC GROWTH

Growth of economic activities is clearly a dominant driver of energy demand. In terms of long-term scenarios, economic growth is usually reported in the form of growth of Gross Domestic Product (GDP) or Gross National Product (GNP). It should be noted, however, that in reality emissions are driven by the individual activities, each measured in their own (physical) units. Monetary values function as an (imperfect) means for aggregation of these activities. Historically, there has been a relatively good correlation between growth of GDP and growth of energy demand, except for periods of strongly rising energy prices. Comparison of GDP data among different sources is somewhat complicated by the relatively large uncertainty, resulting, among others, from aggregation, exchange rates and the influence of base year. The World Bank (World Bank, 2003), the main source of historical GDP data used in our comparisons, does not quantify the associated uncertainties, but indicates that the quality of its data is based on the data that has been reported to the World Bank, and also on aggregation. For growth rates, however, the impact of base year is much smaller.[4] Therefore, we will focus on growth rates rather than the absolute numbers (see Table III for world data and data for the four SRES regions).

For international comparison, data on GDP (or other economic measures) must be converted into a common unit, which is generally done in terms of US$ based on market exchange rates (MER). Purchasing-power-parity estimates (PPP), in which a correction is made for differences in price levels among countries, are considered to be a better alternative for comparison of income levels across regions and countries. Measurement of PPP data, however, is somewhat more problematic, and scenarios expressed in PPP terms are scarce. In SRES, most GDP data are reported in MER terms – although for one model, PPP-based values are also given. Recently, the use of MER-based economic projections in SRES has been questioned (Castles and Henderson, 2003), suggesting that as a result of the use of MER, the economic growth projections in SRES are inflated. SRES authors have argued that the use of MER or PPP data does not in itself lead to substantially different projections for emissions, and that the use of PPP data was at the time impossible due to lack of existing projections (Nakicenovic et al., 2003).

The ensuing debate is not concluded yet. One element of the debate is formed by the purpose of the GDP scenarios, i.e. whether they are projections of the world economy per se or used as an intermediate variable for developing emissions projections. For the former, the debate over the most appropriate measure seems to be the most undecided. Nordhaus (2005), for instance, recommends an intermediate approach, using a PPP-based exchange rate for aggregating across regions, and updating over time using a superlative price index. Timmer, in contrast, prefers the use of MER-data in long-term modeling because data is more available and many international relations are based on MER-exchanges (Timmer, 2005).

If the purpose is to project emissions, it is less likely that the choice of exchange rate will have a substantial effect. Here, monetary units function as means to aggregate the real drivers of emissions, i.e. physical activities. In addition to the aggregated drivers, also an aggregated emission coefficient is calculated by comparing base year emissions with base year economic activity measures in monetary units. The economic activity is then projected into the future as is the development of the emission coefficients. At the end of the simulation period, the two are combined to produce emission levels. If the choice of metric influences the outlook on growth of economic activities, it simultaneously also influences the outlook on development of emission coefficients. Therefore, if a consistent set of metrics is employed, it seems unlikely that the choice of metric will substantially affect emissions.

Nevertheless, results from modeling studies have been contradictory: Manne and Richels (2003) found a small effect of switching from MER- to PPP-based measures, while McKibben et al. (2004) found substantial differences in outcomes. However, results critically depend on the convergence assumptions employed, and it is not clear that all relationships within the models have been adjusted to be consistent with the change in metric. Holtsmark and Alfsen (2004) showed that in their simple model consistent replacement of the metric for economic activities expressed in monetary terms (PPP for MER) throughout the model – for income levels, but also for underlying technology relationships – leads to a full cancellation of the impact. On the basis of these studies, we conclude that using PPP-based values instead of MER-based values would at most only mildly change results in terms of physical parameters, such as energy use or greenhouse gas emissions.

At the global level the choice of PPP versus MER estimates also influences global economic growth rates, since using PPP values implies a larger contribution of low-income countries to global GDP, and thus also increases the contribution of their higher growth rates to the global average increase. MER-based and PPP-based growth estimates can therefore not be directly compared at the global level. In order to compare growth rates of studies that reported in PPP values (IEA, for instance), their growth rates were first assigned to MER-income estimates on a regional basis in the base year.

3.2.1. *Historical Trends*

The historical data used (WorldBank, 2003) indicates an overall 13% growth between 1990 and 2000 in per capita GDP.[5] In general, there is a reasonable agreement with the data reported for the four SRES scenarios and the historical trends. In absolute numbers, there are larger differences (due to the different data sources). All SRES scenarios included the economic downturn in the REF region and the fast growth rates in the Asia region. There are, however, a few quantitative differences. According to World Bank data, GDP in the REF region declined by 22% between 1990 and 2000. The A2 and B2 marker show a somewhat larger decline, while the A1 and B1 scenarios show a smaller decline than the historic data. In the Asia region, the A2 and B2 markers show higher economic growth rates than historical data. Finally, the A2 scenario shows too low growth rates in the OECD. But overall, it can be concluded that the SRES scenarios captured the direction and the relative magnitudes of growth rates across the four regions reasonably well (Table III).

TABLE III
Comparison of SRES per capita GDP trends with 1990–2000 data (in US$ per capita)

		WB-data	A1	A2	B1	B2
		1990 US$				
1990	OECD	19777	19092	19154	20651	19092
	REF	2329	2663	2153	2427	2663
	Asia	532	536	358	503	536
	ALM	1800	1594	1964	1632	1594
	World	4128	3972	3805	3977	3972
2000	OECD	23333	22307	20260	23793	23035
	REF	1828	1909	1900	1632	2410
	Asia	871	828	698	832	1078
	ALM	1985	1779	2222	1941	1787
	World	4656	4365	4084	4378	4646
Ratio 2000/1990	OECD	1.18	1.17	1.06	1.15	1.21
	REF	0.78	0.72	0.88	0.67	0.90
	Asia	1.64	1.54	1.95	1.65	2.01
	ALM	1.12	1.12	1.13	1.19	1.12
	World	1.13	1.10	1.07	1.10	1.17

Source. (Nakicenovic, 2000; WorldBank, 2003).

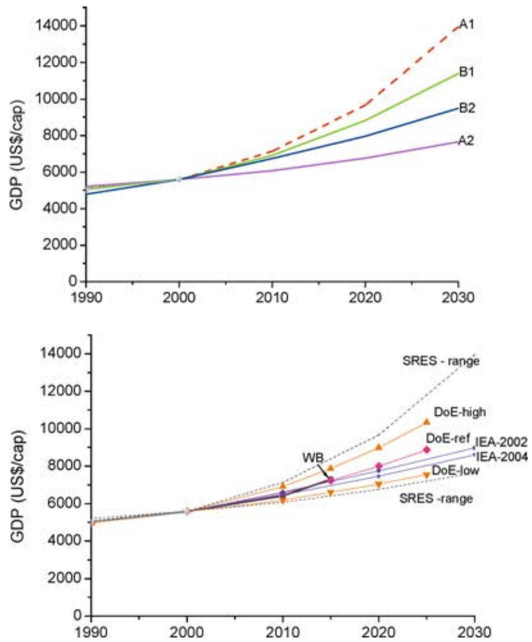

Figure 2. Comparison of global GDP growth in the SRES scenarios and more recent projections. SRES = (Nakicenovic, 2000), WB = World Bank (WorldBank, 2004), DoE = assumptions used by US.Department of Energy (US.DoE, 2004a), IEA assumptions used by IEA (IEA, 2002; IEA, 2004). *Note*: In order to allow comparison, for all studies reported regional growth rates were used on the basis of World Bank data (in market exchange rate 1995 US$) for base year (2000).

3.2.2. *Recent (Near-Term) Projections*

As points of comparison for economic projections, we have used the World Bank's Economic Prospects 2004 (WorldBank, 2004), and the economic scenarios included in the 2002 and 2004 World Energy Outlook (IEA, 2002;IEA, 2004) and the International Energy Outlook (US.DoE, 2003) (Figure 2). In the 2004 version, the economic scenarios of IEA's World Energy Outlook are based on OECD, World Bank and IMF short-term projections, while in the long-term, growth rates for each region are assumed to converge to a long-term rate based on demographic and productivity trends. The economic scenarios of the US.DoE's International Energy Outlook are on a country base developed by Global Insight, Inc. (2003), except the USA for which official US projections are used. The US.DoE outlook includes two alternative projections (low and high), based on alternative assumptions with respect to economic growth: depending on the type of country between 0.5% and 1.5% was added/subtracted to the annual growth rate.

The world economic growth projections included in the World Energy Outlook between 1994 and 1998, particularly in the short term, have been revised slightly upward in each consecutive edition of the outlook (where projections are around 3.0% global growth, measured in PPP$). In fact, real growth rates turned out to be on average 0.5% higher than the assumptions. From the 1998 edition up to the present, growth rates have been revised downward to some extent. The five most recent World Bank projections published between 2000 and 2004, show a downward trend in growth rates anticipated for the 2000–2010 period. For example, in the group of low-income countries the 2000–2010 per capita growth rate was projected to be around 3.8% per year in the 2000 edition and 3.4% in the 2004 edition. This revision was due to relatively slow growth of the world economy between 2001 and 2003, while the longer-term projection remained more-or-less the same. Similarly, between the 2003 and 2004 edition, the Department of Energy's central projection was revised downward from 2.1% to 1.8% annually over the projection period. Its high projection was revised even more, from 3.3% to 2.5% annually, also implying a decrease in the uncertainty range (US.DoE, 2003;US.DoE, 2004a).

The SRES scenarios project a very wide range of global economic growth rates from 1.0% (A2) to 3.1% (A1) (based on MER). This range is somewhat wider than the range covered by the US.DoE high and low scenarios (1.2–2.5%). The central projections of US.DoE, IEA and World Bank all note growth rates of around 1.5–1.9%, thus occurring in the middle of the range of the SRES scenarios (near the B2 trajectory). Other medium-term energy scenarios are also reported to have growth rates in this range (IEA, 2004). It should be noted that although the SRES A1 scenario lies outside the range of the scenarios included here, it is equal to US.DoE's 2003 high-growth projection.

A similar picture emerges at the regional scale (Figure 3). The range of the SRES scenarios is generally consistent with the more recent studies, but there are some important differences. For the OECD and the REF regions, the correspondence between SRES outcomes and recent scenarios is relatively good, although the SRES GDP growth rates are somewhat conservative. This is certainly the case for the low-growth SRES scenarios for the REF region (2% growth rate) compared to the more recent projections (ranging from 3–6%). For the REF region, all scenarios (both SRES and alternatives) show a clear contrast to the negative growth in the 1990–2000 period, which was caused by the economic restructuring process. In the Asia region, the SRES range and its median value have a small upward bias compared to recent studies. This can be explained by the explicit assumption of the A1b storyline that further globalization and rapid technology progress could lead to high growth rates in low-income countries consistent with the high growth rates in East Asia during the late 1980s and 1990s (above 5%). In fact, the B2 growth rates are also considerably higher than the current medium estimates. As the uncertainty bars indicate, some of the non-marker SRES scenarios (in particular for A1) project lower growth rates – making the range of SRES even more consistent with the current projections. The differences between the SRES outcomes and more recent projections are largest in the ALM region. Here, the A1 and B1 scenarios clearly lie above the upper end of the range of current projections (4–5%), while A2 and B2 fall near the center of the range (1.4–1.7%). The 1990–2000 growth rate for this region was 1.0% – and current short-term projections range from 1.1–2.4%.

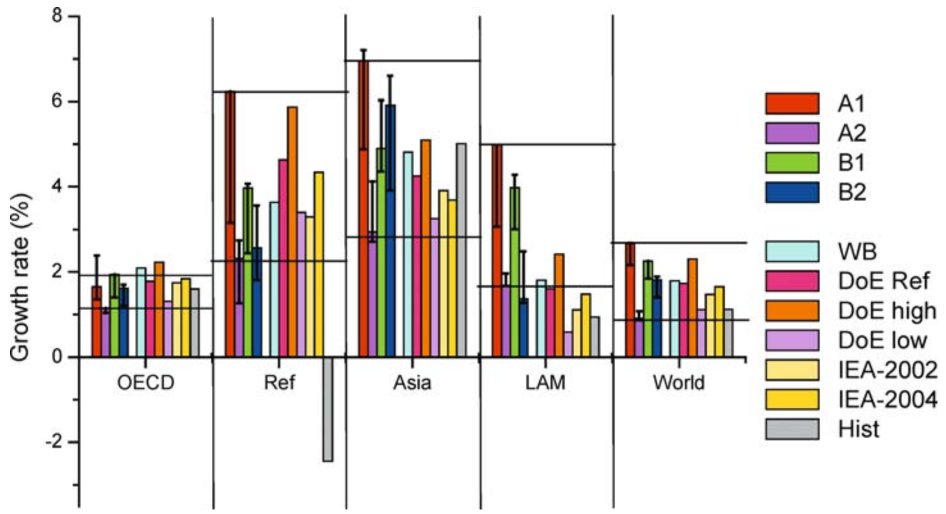

Figure 3. Comparison of the regional GDP annual average growth rate between 2000–2015 in the SRES scenarios and more recent studies. WB = (WorldBank, 2004), DoE = Reference, high and low scenario of US.DoE (2004a), IEA = International Energy Agency (IEA, 2002;IEA, 2004). Hist = Historic data from World Bank (2003). *Note*. The horizontal lines in the figure indicate the range of growth rates set out by the SRES marker scenarios. The vertical lines showing uncertainty bars for the SRES scenarios indicate the range of different outcomes of SRES scenarios within the same family (while the bars indicate the growth rates of the Marker scenarios). The historical rate represents the 1990–2000 period.

Again, the storyline of A1 and B1 emphasizes rapid economic growth in developing countries; however, one could question whether the conditions for growth in the ALM region can be achieved in this relatively short time period. Apparently, the recent short-term projections used here expect current barriers to economic growth in these regions to slow down growth, at least until 2015. Projections from SRES scenarios other than the marker in each family contain somewhat lower growth rates for A1 and B1.

An important axiom in the A1 and B1 scenario is that economic growth will be faster in low-income countries than in high-income countries (leading to partial convergence). The literature on convergence and economic growth, also discussed in the SRES report, indicates a relationship between degrees of governance, stages of development and the potential for economic growth (Nakicenovic, 2000). In the more recent projections, the same trend is found in the relative growth rates of the OECD, REF and Asia regions; however, the ALM region is an exception. Specific barriers (such as lack of good governance, the AIDS crisis, or the dependency on foreign finance) in this region apparently lead current economic projections to assume that this regions will not yet experience an economic take-off similar to what the East Asian economies achieved over the past two decades (WorldBank, 2004).

Overall, our comparison shows that the full range of the SRES scenarios seems to comply relatively well with the most recent medium-term projections. Consistency at the global level is generally good. Although the A1 scenarios fall just above the range of current projections, the full set of SRES projections spans a modestly larger range than the recent projections included here. At the regional level, consistency is also generally good, with the exception of the ALM region. In that region, the degree of rapid economic growth assumed under A1 and B1 scenarios in the next two decades (and to a lesser degree the A1 scenario in the Asia region) is inconsistent with the range of current projections. In addition, the assumptions of the SRES low-growth scenarios for the ALM region, rather than representing the low end of a plausible range, could themselves be considered as still rather optimistic. On a global scale, this means that A1 is somewhat outside the range of current projections.

3.2.3. *Recent Projections for the Long-Term*

There are no official organizations that publish long-term economic scenarios. The only available information comes from individual economic modelling teams active in the field of climate change research, who develop long-term economic scenarios as part of their work. Some groups cooperate within the context of the Energy Modelling Forum (EMF). These scenarios are meant as medium scenarios – and do not intend to explore the upper or lower range of possible growth rates. Richels et al. (2004) published long-term economic projections with uncertainty ranges. Figure 4 shows the A1 and B1 scenarios to be clearly situated above the medium growth projections of EMF-21. The A1 scenario is also found just outside the range of economic growth scenarios of Richels et al. (2004). The B2 scenario seems to be reasonably representative of medium-growth scenarios. For A2, it should be noted that low economic growth in SRES is combined with rapid population growth, causing the somewhat upward bias compared to current low-growth projections. Apart from this, the A2 scenario seems to be representative of current low-growth scenarios for per capita income.

3.2.4. *Credibility of SRES Assumptions*

The comparisons show that while the SRES scenarios are largely consistent with current projections at the global level, the set represents mainly high-growth scenarios for the ALM region in the first decades. As a result, the global growth trend in the first few decades of the A1 scenario lies outside the range of current projections. Whether this has longer term implications for the scenario is unclear. A slower start in economic growth than assumed in the A1 scenario could put the region on a growth path that is permanently separated from the high-growth projections (i.e. the implications are persistent into the long term), but could also mean a delay without substantial long-term consequences. While updates of SRES might want to focus on variants that delay high economic growth rates in the ALM region and that include a slow global economic growth scenario, the current inconsistency in

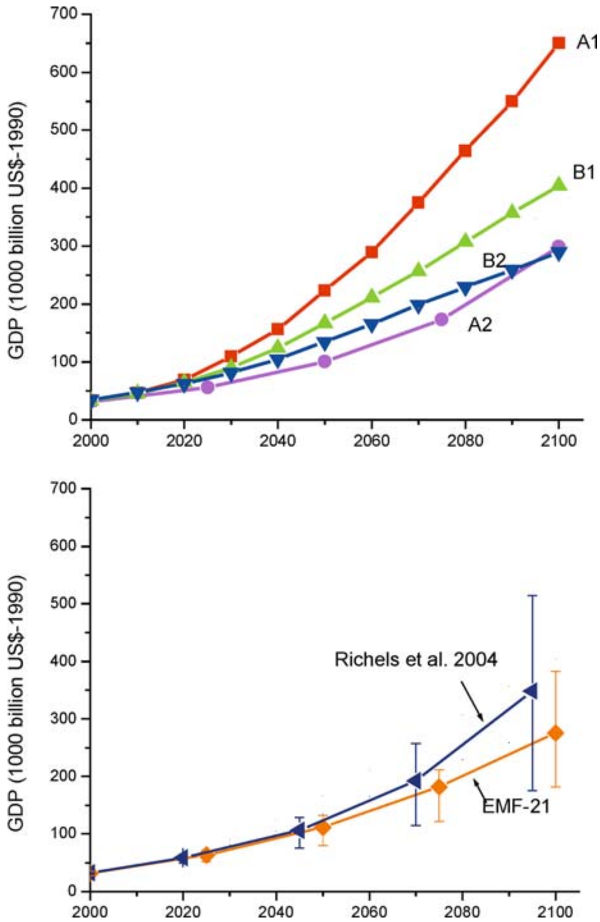

Figure 4. Comparison of the SRES scenarios with the range of GDP projections used in recent long-term scenario studies. The range in EMF-21 (Weyant et al., 2005) indicates the lowest and highest projection included in a set of baseline projections of different models. The range for Richels et al. (2004), represents the 5th and 95th percentiles of the distribution in that study.

the ALM region might only be a problem in using the SRES scenarios for this specific region. With respect to global application, the contribution of the ALM region to global greenhouse gas emissions in the short term will be small, even under high-growth assumptions.

3.3. ENERGY USE

3.3.1. *Historical Trends*

For energy use, we compared the changes in SRES primary energy use between 1990 and 2000 to the estimates included in IEA's Energy Balances and Statistics for OECD and non-OECD countries (IEA, 2003b) (Table IV). It should be noted

TABLE IV
Comparison of SRES trends in primary energy use with 1990–2000 data (in EJ)

		IEA	A1	A2	B1	B2
1990	OECD	172	167	155	151	159
	REF	70	71	67	95	70
	Asia	71	80	53	79	74
	ALM	45	58	38	43	49
	World	358	376	313	368	352
2000	OECD	201	191	176	178	180
	REF	50	51	45	52	62
	Asia	100	100	82	113	103
	ALM	62	82	57	64	63
	World	413	424	360	407	408
Ratio 2000/1990	OECD	1.17	1.14	1.14	1.18	1.13
	REF	0.70	0.72	0.67	0.55	0.89
	Asia	1.41	1.25	1.55	1.43	1.39
	ALM	1.38	1.41	1.50	1.49	1.29
	World	1.15	1.13	1.15	1.11	1.16

Source. (Nakicenovic, 2000; IEA, 2003b).

that the absolute difference between A2 and the IEA data is caused by the fact that the former does not include the use of traditional biofuels.[6] As a result, growth rates in low-income regions in the SRES A2 scenario as well are higher, resulting from the substitution of traditional fuels with commercial fuels. In terms of trends, there are only a few differences between historical trends and those included in SRES. These differences are consistent with (and possibly a result of) the differences in GDP trends that were observed earlier: B1's lower energy increase for the FSU, and A1's lower and A2's higher increase for Asia.

3.3.2. *Recent (Near-Term) Projections*

Figure 5 shows that the range covered by the set of near-term projections nearly capture that of SRES, and that the projections from IEA's World Energy Outlook (IEA, 2002) and US.DoE's central projection (US.DoE, 2004a) are near the SRES median.[7] The A1 scenario is somewhat above the range, while the US.DoE low economic growth scenario follows a trajectory somewhat below the lowest of the SRES scenarios (B2). The higher energy consumption in A1 is consistent with its higher income growth (as observed earlier). Because the results for energy are very similar to those for CO_2 emissions, regional trends are discussed only for the latter.

3.3.3. *Credibility of SRES Assumptions*

The results for energy are consistent with our earlier finding for GDP assumptions in SRES. SRES reflects historical trends reasonably well, and compares well on a global scale with near-term projections in recent studies. The energy use in the A1 marker scenario lies somewhat above the range of near-term projections and therefore might be considered somewhat less likely than other scenario outcomes,

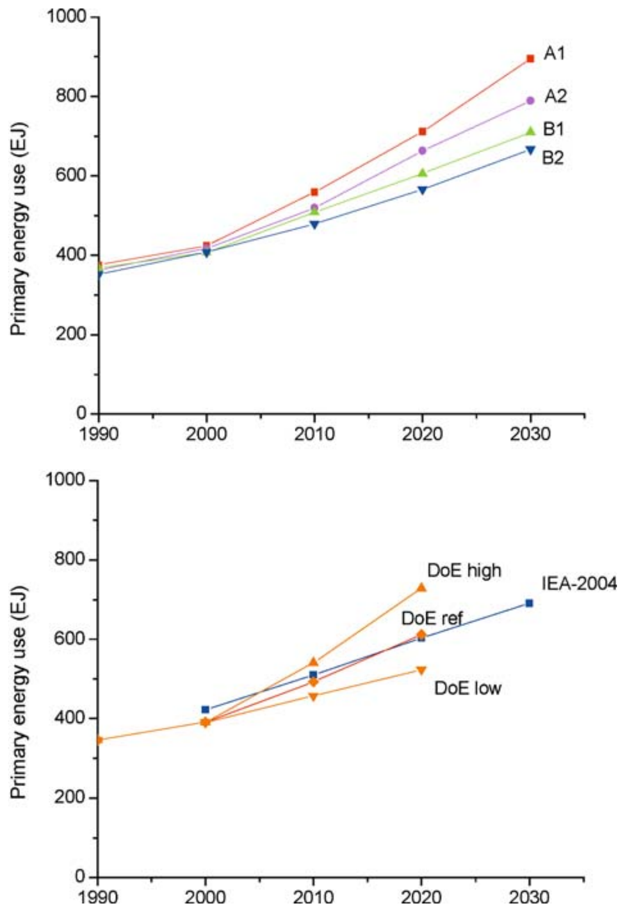

Figure 5. Comparison of trends in SRES total primary energy consumption and more recent studies by US.DoE and IEA. DoE = Projections from US. (2004a) DoE, IEA–2004 = Projection from the International Energy Agency. (IEA, 2004). *Note*. Original A2 scenario as reported in SRES does not contain non-commercial biomass use. Therefore A2 non-biomass data has been taken from IEA energy data – and held constant after 2000.

although a specific conclusion cannot be drawn, given that the high end of the range of recent projections is defined by an EIA scenario that is not associated with any judgement of likelihood by the developers.

4. Results for Emission Projections

For all the published emissions data, the SRES report used a standardization process (see methodology). This means that the comparison in the historical period is done for the standardized 1990–2000 data (and not for individual model results).

4.1. CO_2 EMISSIONS FROM ENERGY AND INDUSTRY

4.1.1. *Historical Trends*

Emission estimates are affected by inevitable degrees of uncertainty. The SRES report reviews the relevant literature, which gives a range from 6.0 to 8.2 GtC for total CO_2 emissions in the year 1990 (compared to a standardized value of 7.1 GtC retained for the SRES scenarios) (Nakicenovic, 2000). By far the largest part of this uncertainty range is attributable to emissions from land-use change, although for industrial sources of CO_2 emissions (fossil fuel burning, flaring of natural gas and cement manufacturing) some uncertainty also exists. Some of the differences between the different data sources on CO_2 emissions come from differences in coverage (often cement manufacturing, bunker emissions and feedstocks are not included), but also from differences in underlying energy data, detail in energy carriers, and emission factors. Olivier and Peters (2002) show that revisions in different databases for the last few years of published data create an error for that year of 1–8%. The total uncertainty in the EDGAR CO_2 emission inventory is estimated to be around 10% (Olivier, 2004). Here, we will focus on the emissions from energy and other industrial sources on the basis of the most recent emission inventories (see Table V).

Table V illustrates the uncertainties in past and current emission estimates by showing the difference between the various inventories. Of these sources, IEA and

TABLE V
Emission inventories of industrial CO_2 emissions (in MtC)

		1990	1999	2000	Growth 2000–1990	Ratio 2000/1990
Fossil fuel combustion	CDIAC	5925	6242	6353	428	1.07
	EDGAR	6078	6608	6700	622	1.10
	IEA	5980	6558	6738	758	1.13
	US.DoE	5928		6468	540	1.09
Total, including cement	CDIAC	6126	6492	6611	485	1.08
	EDGAR	6297	6877	6972	676	1.11
	IEA$^+$	6144	6776	6973	829	1.13
	US.DoE$^+$	6092		6703	611	1.10
	SRES	5999		6896	897	1.15

Note. Figures do not include emissions from non-energy use of fossil fuels (e.g. feedstocks). Numbers include gas flaring and emissions from international bunkers, coming to approximately 50 and 200–300 $MtCO_2$, respectively.
$^+$ The US.DoE and the IEA inventories do not include emissions from cement productions. For them, emissions from these sources have been estimated on the basis of USGS production figures.
Source. (Nakicenovic, 2000; Olivier and Berdowski, 2001; IEA, 2003a; Marland et al., 2004; US.DoE, 2004b).

EDGAR are the most detailed. Absolute emissions in 2000 according to SRES are within the literature range, although SRES emissions in 1990 are somewhat below the currently estimated range for that year. The increase in the SRES emissions between 1990 and 2000 (15%) is somewhat higher than in any of the currently available global emissions inventories (which range from 8–13%).

The underlying regional data (not shown) indicate small differences in emission growth rates for the OECD, REF and ALM regions. In contrast, there is a larger difference in the Asia region (45% increase in IEA and EDGAR versus a 55% increase in SRES). The 'overestimation' in CO_2 increase in this region in SRES results from expectations in the late 1990s that Chinese emissions would continue to grow rapidly. In reality, emissions growth in China has probably been relatively slow in the second half of the 1990s. However, development of Chinese CO_2 emissions during this period has been subject to debate. In the early 2000s, some data sources (e.g. CDIAC) indicated a decline of Chinese emissions in the late 1990s caused by both a slow down of economic growth and Chinese reform of the coal market – in particular closing small mines. These effects were regarded as temporary, and unlikely to affect long-term emission trends (Van Vuuren et al., 2003). Since then historical data on coal use during the late 1990s has been revised upwards (decreasing the difference with the SRES figures). This uncertainty in Chinese emissions is one important cause of the differences between the global emission inventories.

Given the uncertainties within the inventories, the overestimation of global CO_2 emission increase in SRES can either be regarded as acceptable, when compared to the IEA, US.DoE and EDGAR inventories, or considerable, when compared to the CDIAC numbers, which indicate only an 8% growth.

4.1.2. *Recent (Near-Term) Projections*

The IEA and US.DoE projections are again used as references for expected near-term trends. In addition, we use the highest and lowest projections from the Energy Modelling Forum (EMF-21) (Figure 6). These scenarios (called the 'modeller's preference baseline') represent 'medium'-growth scenarios, and the range should be interpreted as an indication of how different modelling groups, using different models, assess the range of such medium projections.[8] The comparison shows results similar to those for energy projections. In most cases, the SRES emission scenarios are consistent with near-term projections. A clear exception is formed by the high-economic growth A1 scenario, which is above the range, especially around 2010. After 2010, the differences between the A1 projection and the high-growth US.DoE projection decline, and almost converge in 2025. The IEA 2004 baseline projection, the US.DoE's reference scenario and the EMF-21 range are all found near the more central projections of SRES (with the IEA-2002 projection displaying virtually the same emissions).

On a regional scale, comparison confirms the results for the main emissions drivers found earlier (Figure 7). For the OECD region, emissions increases in the

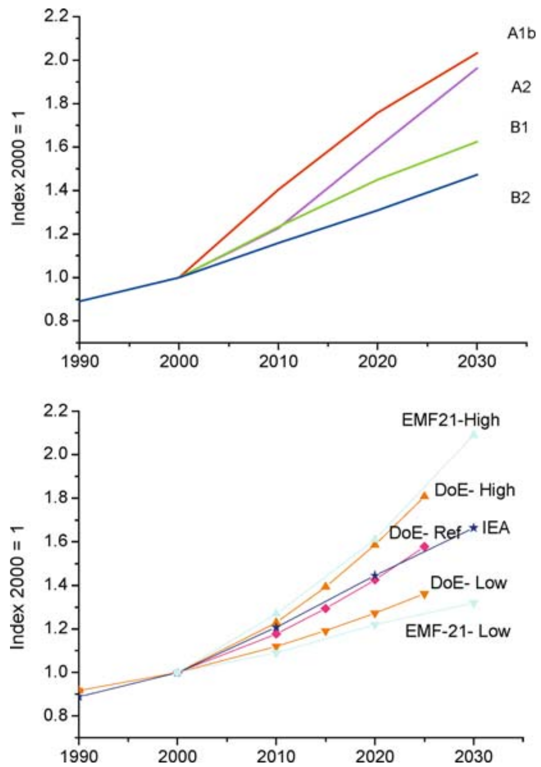

Figure 6. Comparison of trends in global CO_2 emissions, SRES versus more recent projections. DoE = Projections from US. DoE (2004a), IEA = Projection from the International Energy Agency. (IEA, 2004). EMF-21 indicates the range of the lowest and highest reported values in the EMF-21 study (Weyant et al., 2005).

SRES scenarios are somewhat lower than those in the studies used for comparison. This is, in particular, the case for B1 (likely to be a result of the emphasis on environmental protection), but also for A1 (possibly due to swift technology development and less coal use). The highest projections of the SRES range (A2) more-or-less coincide with the central US.DoE and IEA projections. A similar situation holds for the REF region.

In the Asia region, the range of the SRES scenarios lies somewhat above that of the more recent projections, but differences are small. The most important ones are found for the ALM region, for which the A1, B1 and A2 scenarios clearly project a somewhat faster increase than more recent projections. This reflects the fairly high GDP and energy growth assumptions for this region discussed above, which are part of the A1 and B1 storyline by design. Since the ALM region produces a relatively small share of global emissions, the impact on global results is limited.

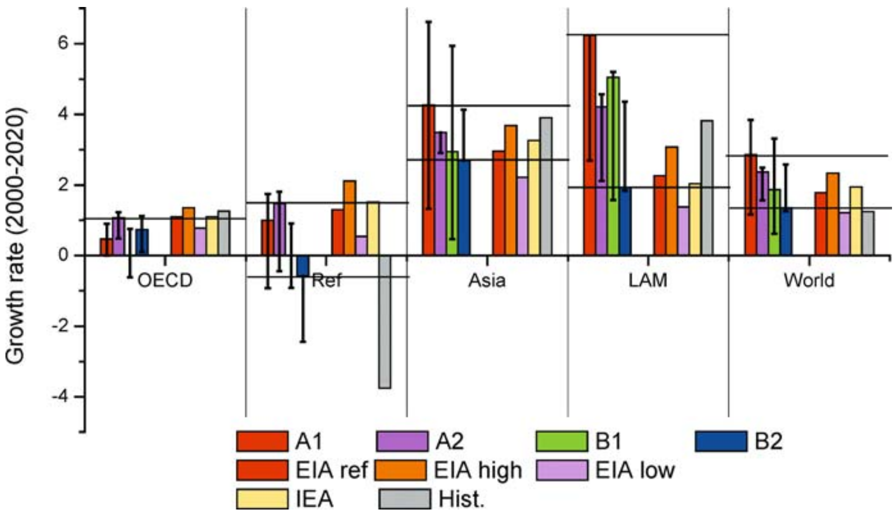

Figure 7. Comparison of trends in regional CO_2 emissions, SRES versus more recent projections (2000–2020 annual average growth rates). DoE = Projections from US. DoE (2004a). IEA = Projection from the International Energy Agency (IEA, 2004).. Hist = Historic data from the IEA energy database. *Note*. The horizontal lines in the figure indicate the range of growth rates set out by the SRES marker scenarios. The vertical lines showing uncertainty bars for the SRES scenarios indicate the range of different outcomes of SRES scenarios within the same family (while the bars indicate the growth rates of the Marker scenarios). The historical rate represents the 1990–2000 period.

4.1.3. *Long-Term Projections*

As in the case of GDP, there are no official institutions publishing long-term CO_2-scenarios independent of SRES. Instead we use scenarios from individual modelling groups (Figure 8), taken from the EMF-21 set (Weyant et al., 2005) (upper panel) and the two available studies that have estimated probability ranges (Webster et al., 2002; Richels et al., 2004) (lower panel). For the comparison with the EMF-21 set, again it should be noted that most of these scenarios represent trends considered to be medium trends by the individual modelling teams. Taken collectively, the set of SRES scenarios lies somewhat below the EMF-21 set – with the B1 scenario standing out as being much lower than the EMF-21 range. The B1 scenario is based on the intention to explore the consequences of sharp increases in efficiency and environmental technology (driven by environmental policies other than climate policies). The comparison with the set probabilistic projections show a similar result: the SRES scenarios cover a similar range, with the mean and range of the SRES set at somewhat below the range of other two other studies.

4.1.4. *Credibility of SRES Assumptions*

For CO_2, the comparison of the SRES scenarios with more recent information shows that the SRES scenarios are generally consistent with historical data on the magnitude of current emissions, and with the range of recent projections. There are a few noteworthy exceptions. First, in the 2000–2025 period, the global results for the

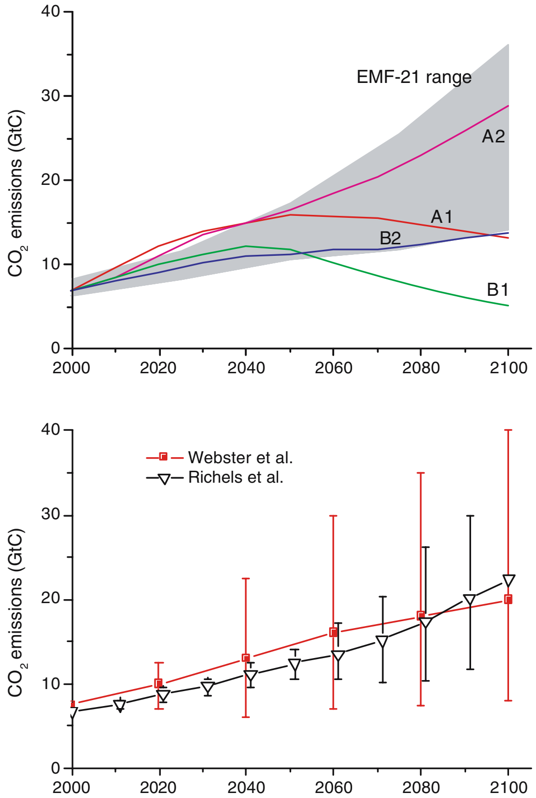

Figure 8. Comparison of the SRES scenarios to recent long-term scenarios for CO_2 emissions. 'EMF-21 range' (grey area) indicates the range of the lowest and highest reported values in the EMF-21 study (Weyant et al., 2006). Webster et al. (2002) and Richels et al. (2004) indicate the mean (markers) 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).

A1 scenario are significantly higher than current projections. Second, the complete set of SRES scenarios shows an upward bias for the ALM region compared to recent projections. However, these two exceptions do not seem to lead to an upward bias in the long term. In fact, the SRES scenarios cover a range that is even somewhat below the range of recent long-term studies.

4.2. NON-CO_2 GREENHOUSE GASES

4.2.1. *Historical Trends*

Uncertainties in current inventories are larger for non-CO_2 gases than for CO_2, since non-CO2 gas emissions are driven to a much greater extent by diffuse agricultural sources (with high uncertainty). The most reliable source of historical data is the EDGAR historical database (Olivier and Berdowski, 2001).

Worldwide, methane emissions have been virtually stable in the 1990–2000 period (1% increase). This global trend is, in fact, a net result of increasing emissions in developing countries and decreasing emissions in the Former Soviet Union. The SRES scenarios actually assumed a small increase in the 1990–2000 period (+7%). In EDGAR, the total uncertainty for annual methane emissions was estimated at plus and minus 23% of the mean value – coming, in particular, from uncertainty in emissions from animals and rice cultivation (Olivier and Peters, 2002). Given the uncertainty in methane emissions, the difference between SRES and the historical estimate cannot be taken as statistically significant. For N_2O, SRES and EDGAR indicate nearly the same rate of increase (6% and 7%, respectively). The comparison is complicated by different definitions on anthropogenic versus natural emissions.[9] The uncertainty in N_2O emission inventories is considered to be substantially larger than for CH_4, i.e. about 50–100 % (Olivier, 2004).

There is a substantial difference between the SRES data and current 1990–2000 emission estimates for emissions of the halocarbons (HFCs, PFCs and SF6). In fact, at the time SRES was developed, relatively little was known about emissions of these gases. Since then, considerable attention has been paid to updating the emissions inventories for these gases. However, uncertainty levels are still judged to be about 50–100 % in the EDGAR database (Olivier, 2004).

4.2.2. *Recent (Near-Term) Projections*

The most useful comparison for medium-term term projections of non-CO_2 emissions is found in the recent projection made by Scheele and Kruger (2006) on the basis of national communications to UNFCCC and expert judgement. Figure 9 shows that the SRES scenarios compare well to the current near-term projection. For most gases, particularly N_2O, the SRES scenarios show slightly lower growth rates than the scenario of Scheele and Kruger (2006), which is consistent with the fact that the latter does not assume any technological progress in emission factors, while SRES scenarios do include some improvement. The same conclusion holds for the emissions of HFCs, SF6 and PFCs.

4.2.3. *Long-Term Projections*

In the context of EMF-21 a major modelling effort was made to update the capability of long-term integrated assessment models for modelling non-CO_2 gas emissions. It should be noted, however, that the majority of the models involved are energy–economy models – and therefore less well-equipped to model non-CO_2 emissions, which result mainly from agricultural activities. Some of the models involved in EMF-21 (in particular IMAGE, AIM, MiniCam and MIT) have a more detailed representation of agricultural drivers. We have used all model outcomes of EMF-21 as an indication of the range of model outcomes to date, but note that the 'more detailed' models mentioned above tend to cluster in the middle of this range. Nonetheless, results show that the trend and range of the SRES scenarios strongly coincides with the trends and ranges in the EMF-21 study (Figure 10). In general,

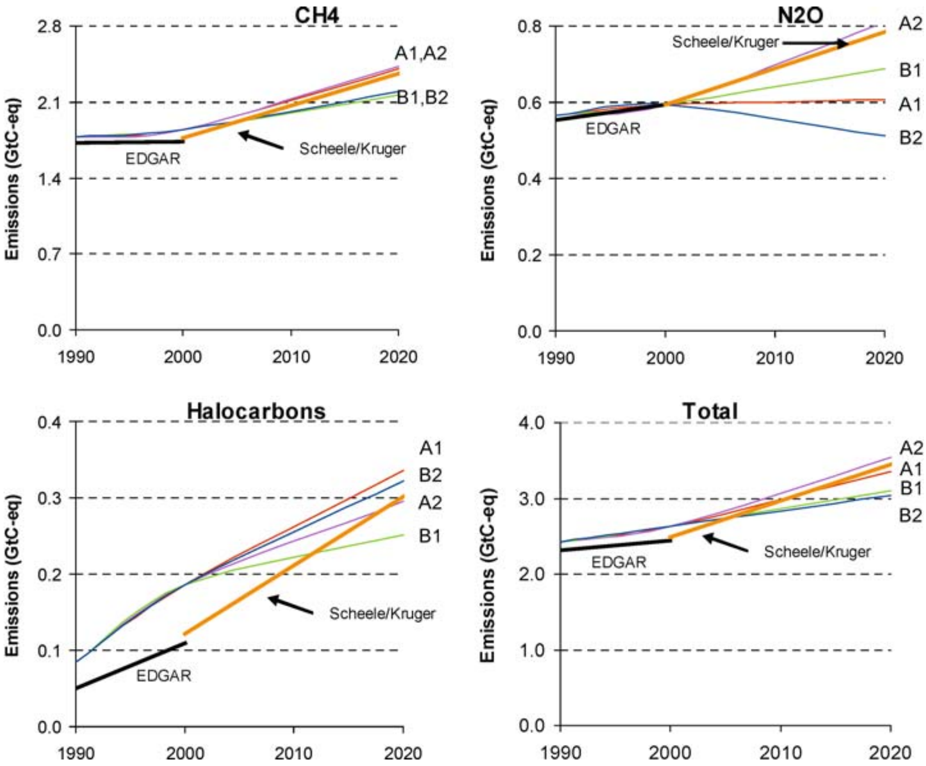

Figure 9. Comparison of trends in global non-CO_2 emissions, SRES versus more recent projections. EDGAR indicates the historic data included in the EDGAR database (Olivier and Berdowski, 2001), Scheele/Kruger indicates the projections of Scheele and Kruger (2006).

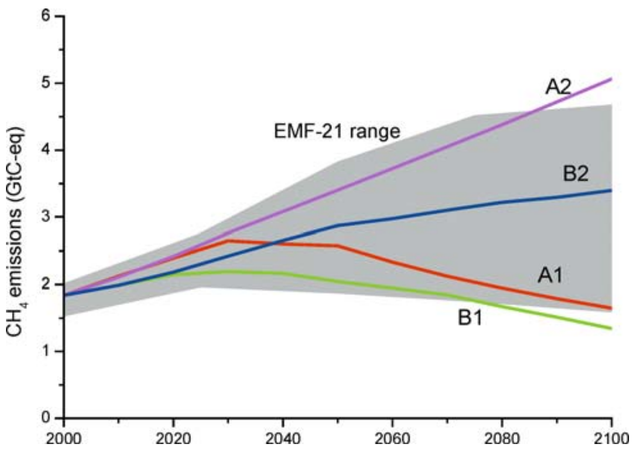

Figure 10. Long-term trends in methane emissions, SRES versus more recent projections (EMF-21). EMF-21 indicates the range of the lowest and highest reported values in the EMF-21 study (Weyant et al., 2005) *Note*. The results of one model have not been used to indicate the EMF-21 range, as the emissions of this model clearly form an outlier within the total set (emissions increase to 11 GtC-eq).

methane and nitrous oxide in both SRES and EMF-21 display somewhat slower growth rates than CO_2 emissions as these emissions are coupled, in particular, with agricultural drivers – which show lower growth rates than energy drivers (important for CO_2).

4.2.4. *Credibility of SRES Assumptions*

The SRES scenarios seem to be fully in line with more recent projections for the non-CO_2 greenhouse gases.

4.3. SULFUR EMISSIONS

4.3.1. *Historical Trends*

Aerosols from sulfur emissions can have a significant cooling effect and therefore form an important element of the SRES scenarios. Table VI shows the 1990–2000 sulfur data according to three different estimates (Amann, 2002; Stern, 2003; Smith et al., 2004a) in comparison to the assumptions included in SRES. It should be noted that here again, there is considerable uncertainty involved in sulfur emissions inventories, mainly with regard to the degree to which desulfurization technology is applied in different regions. Qualitative uncertainty estimates amount to 10–50% (Olivier, 2004). As for CO_2, a major cause of uncertainty in the late 1990s is the uncertainty involved in the coal use trend in China. While some sources assume a decline in coal use in the late 1990s, others only indicate a stabilization of coal use.

TABLE VI
Emission trends for sulfur emissions 1990–2000 (in Tg S)

		Stern (2003)	Smith et al. (2004a)	Amann (2002)	SRES
1990	OECD	22.4	22.6	33	22.7
	Ref	16.0	17.1	14	17.0
	Asia	16.2	17.8	16	17.7
	ALM	8.0	10.3	9	10.5
	World	62.6	70.8	72	67.9
2000	OECD	16.5	14.5	19	17.0
	Ref	6.5	8.5	11	11.0
	Asia	18.8	23.9	16	25.3
	ALM	10.1	10.6	10	12.8
	World	51.9	57.5	57	66.1
Ratio 2000/1990	OECD	0.74	0.64	0.60	0.75
	Ref	0.41	0.50	0.78	0.65
	Asia	1.16	1.34	1.00	1.43
	ALM	1.26	1.03	1.13	1.22
	World	0.83	0.81	0.79	0.97

In SRES, worldwide sulfur emissions were assumed to decline by 3% in the 1990–2000 period, the net result of a clear decrease in the OECD and REF regions, and a considerable increase in Asia and the ALM region. Studies that estimate actual trends in that period now find that worldwide emissions actually decreased by a much larger amount (around 20%). The main reasons for this difference are a faster decline in the REF region (than assumed in SRES) and a slower increase in Asia. Again, a considerable part of the differences can be attributed to assumed lower coal use in China between 1998 and 2000, but actual trends are highly uncertain. In the ALM region, the projected SRES emission increase lies between that of Smith et al. (2004a) and Stern (2003).

4.3.2. *Recent (Near-Term) Projections*

The SRES scenarios can be compared against more recent near-term projections of Amann (Amann, 2002) and Smith (Smith et al., 2004b). The projections of Amann (up to 2020) were made on the basis of existing country-level projections and reduction plans,[10] but did not include all countries. Therefore, the data set was extended to the global level using 2000 emissions levels from (Stern, 2003), assuming similar growth rates as for those regions for which data was directly available. The work from Smith (Smith et al., 2004b) is based on the MiniCam model (one of the SRES models) and uses the SRES storylines. However, as the model has been fully recalibrated on the basis of new historic emissions data, the study can be regarded as an independent source.

The comparison (Figure 11) shows that the highest of the SRES projections appear to be very high (this certainly holds for A2 and for the first 20 years of A1) and as a consequence rather unlikely. Also, the lower range of the scenarios has shifted

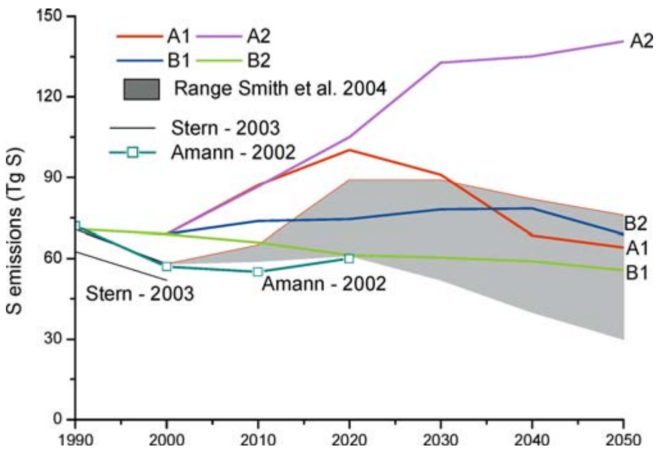

Figure 11. Comparison of SRES sulfur emissions and more recent projections. Data based on (Amann, 2002; Stern, 2003; Smith et al., 2004a).

downwards by about 10–20% or so. At the same time, however, the trends in the Amann study are consistent with the lower SRES scenarios (those assuming more pro-active environmental policies). The insight that worldwide sulfur emissions might not increase as rapidly as a result of desulfurization policies in low-income countries is in fact relatively recent. Interestingly, during the review procedure, the SRES scenarios were actually criticized for including too low sulfur emission scenarios. Compared to all other variables then, the degree of inconsistency of SRES with both historical emission trends and near-term expectations is highest for sulfur emissions. Correction of the SRES emission projections downwards (for A2 and A1) would have an upward effect on the near-term temperature ranges associated with the SRES scenarios.

5. Discussion and Conclusions

We have investigated the consistency of the IPCC SRES scenarios with available 1990–2000 data and recent projections, primarily short-term outlooks. The most important inconsistencies are summarized in Table VII.

In almost all the cases of (now) historical development, the SRES assumptions for 1990 and 2000 are reasonably consistent with available data. This certainly holds

TABLE VII
Main inconsistencies found between the SRES scenarios and more recent scenarios and data

Parameter	Inconsistencies noted in comparison
Population	• SRES does not include a representation of the lowest end of the current range of projections
	• The A2 scenario is significantly higher than the high end of the current range of projections
	• For specific regions (in particular sub-Sahara Africa and China), differences between SRES and current projections larger.
GDP	• Global economic projection for A1 is outside range of current projections in the first 2 decades
	• For the ALM region, the set of SRES scenarios seem to be representative of the upper end scenarios only.
	• No major anomalies with historical data
Energy	• See GDP
CO_2	• See GDP for short-term projections
	• Slightly too high for 2000 emissions
Non-CO_2 gases	• Somewhat too high for the F-gases in 2000
	• Several forcing agents (black carbon) not included yet
Sulfur	• 2000 sulfur emissions too high.
	• Emissions in A1 and A2 substantially above current range of projections in first decades

for the global projections for income, population, energy and non-CO_2 gases. Only small differences were found for these variables on the regional scale, in particular, for income trends and energy trends in Asia and REF. For CO_2 emissions, the SRES scenarios indicate a slightly more rapid global increase between 1990 and 2000 than is now apparent from emission inventories (15% versus an average of 11%), but the difference in terms of absolute emissions in 2000 is small (mostly caused by the decline in coal use in the late 1990s in China). Finally, for sulfur emissions, there seems to be a clear difference between the assumed change in SRES in the 1990–2000 period and the trend in current inventories (a global 3% versus 20% decline, respectively), mostly resulting from diverging trends in the Asia and REF regions. In both the case of CO_2 and sulfur it should be noted that trends in China in the late 1990s are still uncertain.

Comparing the SRES scenarios to current near-term projections shows the SRES scenarios in most cases to be within the range of these projections, both globally and for individual regions. It should also be noted, however, that the range of population and economic projections has shifted downward since SRES publication. While SRES assumptions regarding these drivers in most cases still fall within the range of new literature, in a few cases they rise above it. In addition, the low end of the current range is under-represented in the SRES scenarios for both population and economic growth. Revisions of the SRES scenarios based on the same storylines could therefore be based on somewhat lower population projections and near-term economic projections. This would be more important in particular regions and scenarios. In the case of economic growth, assumptions for the ALM region, the A1 scenario in particular, deserve the most attention. In the case of population, the assumptions for the Asia and ALM regions in the A2 scenario would be the most important to consider for revision since they differ the most from the updated range of projections. In addition, our results show the differences between SRES and more recent population projections for the medium term (2050) are magnified in the long term (2100) due to the path dependency of population growth. Lower population pathways, all else equal, are likely to lead to lower greenhouse gas emissions, and the associated increases in aging may exacerbate this effect (Dalton et al., 2005). For economic growth, the potential impact of lower economic growth scenarios (for the ALM region) is less obvious, as downward revisions of economic growth will also have consequences for technology development and fuel trade. At the same time, it should be noted that except for the first two decades for A1, in terms of emissions the SRES scenarios still seem to be fully consistent with the current range of more recent outlooks.

Comparison on the regional scale shows that the most important differences between SRES and the current near-term projections occur for the ALM region. Here, the range of SRES economic growth assumptions and resulting growth rates for energy use and CO_2 emissions are near or beyond the upper end of current projections. By now, the assumed rapid change in conditions for economic growth in this region seem to have become (even more) questionable. The impact of this region on the global emissions projections is limited. The GDP and emissions growth rates of the Asia region in the A1 scenario are also high compared to the recent projections, although to a much smaller degree.

Another important difference between the SRES scenarios and more recent insights occurs for sulfur. As a result of the rapid decline in global emissions in the 1990–2000 period and expectations about desulfurization policies in low-income countries, a rapid increase in sulfur emissions, as occurs in some of the SRES scenarios for sulfur between 2000 and 2030, has become very unlikely. Despite the fact that the exact trend in Chinese emissions during the 1990s remains an important uncertainty, a revision of scenarios is likely to result in lower sulfur emissions. Other factors being equal, such a revision would imply an increase in the expected short-term temperature change associated with the SRES scenarios.

Finally, there are a few elements that have not been included in the SRES scenarios in much detail and which recently have become much more important for climate change projections. One of these is emissions of black and organic carbon; another is grid-based land-use projections. Non-official projections consistent with SRES assumptions have now become available from individual modelling teams.

Regarding the question of whether the SRES scenarios have become outdated or not, there are obviously no hard criteria. With a few exceptions, the study reported here has shown the SRES trends to still be plausible. In addition, there is no evidence that the underlying axioms of the storylines have been falsified. As a result, at this point in time there seems to be no need for a large-scale IPCC-led update of the SRES scenarios on the sole basis of their performance in the 1990–2000 period, or of a comparison with more recent projections. At the same time, however, individual modelling groups could decide to update their scenarios, making them fully consistent with current trends, while still preserving the connection with the SRES storylines and harmonization criteria. Such an approach has been taken, for instance, by the IMAGE group when it published its detailed elaboration of the SRES scenarios in 2001 (IMAGE-team, 2001). Variants of SRES scenarios could also be developed by independent research teams to cover parts of the range of drivers or outcomes that are less well represented in SRES; the low end of the range of future population size is one example. In fact, the SRES report itself allowed for a great diversity of elaboration of the same scenarios – indicating particular criteria for scenarios to meet in order to maintain consistency. Most of these criteria are formulated for the longer term (first criteria to be applied in 2025). The option of updating SRES scenarios (by individual modeling groups), while upholding the connection with the SRES storylines and criteria, will, in general, keep results compatible with earlier work and allow for more comparability (and easier communication) in assessment (for instance, in IPCC's Fourth Assessment Report). At the same time, the SRES updating option will allow research groups to produce long-term scenarios that are also well suited to shorter term applications.

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Notes

[1]In addition, draft results of the modelling groups were put on a website for comments by outside reviewers. The scenarios were also reviewed by both experts and government representatives.

[2]While in SRES, all results were reported for the four large regions only, each of the models used has a much more detailed regional breakdown. The more geographically detailed results, however, do not form part of SRES as officially adopted and are therefore not included in this review. The regional disaggregation of the different models and their basic set-up are described in the SRES report.

[3]As indicated in the SRES report, the different regional break-down of the different models did not always allow for consistent aggregation into the IPCC regions. In these cases, slightly different region definitions were used. For example, in the IMAGE 2.2 model Mexico is part of the Central America region, and therefore cannot be separately added to the OECD region. The small discrepancies caused by these regional definitions is indicated where relevant in the SRES report – and for some variables can also be seen here.

[4]At the country level, there is a small impact of base year on long-term growth rates. On the regional level, the impact can be somewhat larger as the relative income of different countries (and therefore their weight in the overall growth rate) may be influenced.

[5]The World Bank data is reported in 1995 US$, while the SRES scenarios are reported in 1990 US$. For comparison, the World Bank data has been recalculated into 1990 US$ (at the country level) using inflation and exchange rate derived from the same World Bank data base.

[6]The A2 marker scenario was developed by the ASF modelling team. This model does not calculate traditional biomass numbers; A2 elaborations of other modelling teams do include traditional biofuel projections.

[7]For a description of differences between the reference, low and high projections of US.DoE see the section on GDP growth.

[8]Since the SRES scenarios deliberately choose more extreme assumptions to explore possible alternative futures, one would expect them to fall somewhat outside this range.

[9]This involves, in particular, emissions from agricultural soils. Some studies include all emissions from such soils. Others only include emissions above the level that would have occurred on a natural soil. A further complication is formed by indirect emissions.

[10]Amann's inventory included the OECD, REF and the Asia region. It did not fully include the ALM region. This region has been added here by using 1990 and 2000 figures from Smith et al. and assuming a trend in this region similar to the Asia region.

References

Amann, M.: 2002, 'Emission trends of anthropogenic air pollutants in the Northern Hemisphere', Conference on Air Pollution as a Climate Forcing, Honolulu, Hawaii.

Castles, I. and Henderson, D.: 2003, 'The IPCC Emission scenarios: An economic-statistical critique', *Energy & Environment* **14**(2–3), 159–185 (27).

Corcoran, T.: 2002, 'An insult to science. Leading economists want a full review of the UN's 100-year economic models for climate change, which they say contain "material errors" that invalidate temperature forecasts', *National Post* (November 27).

Dalton, M., O'Neill, B. C., Prskawetz, A., Jiang, L., and Pitkin, J.: 2005, *Population Aging and Future Carbon Emissions in the United States*, International Institute for Applied System Analysis, Interim Report IR-05-025, Laxenburg, Austria. Submitted to Energy Economics.

De Mooij, R. and Tang, P.: 2003, *Four Futures of Europe*, CPB Netherlands Bureau for Economic Policy Analysis, The Hague, The Netherlands.

Gaffin, S. R.: 1998, 'World population projections for greenhouse gas emissions scenarios', *Mitigation and Adapatation Strategies for Global Change* **3**, 133–170.

Global_Insight: 2003, *World Overview*. Global Insight, Inc, Lexington, USA.

Hilderink, H. B. M.: 2004, *(Population & Scenarios, Worlds to Win?* Netherlands Environmental Assessment Agency (RIVM-MNP), Bilthoven, the Netherlands.

Holtsmark, B. J. and Alfsen, K. H.: 2004, 'PPP-correction of the IPCC scenarios: Does it matter?' *Climatic Change* (Accepted for publication).

Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell K., and Johnson, C. A.: 2001, *Climate Change 2001: The Scientific Basis*, Cambridge University Press, Cambridge.

IEA: 2002, *World Energy Outlook 2002*. International Energy Agency, Paris.

IEA: 2003a, *CO2 Emissions from Fuel Combustion 1971–2001 – 2003 Edition*. International Energy Agency, Paris.

IEA: 2003b, *Energy Statistics of OECD countries / Energy Statistics of non-OECD countries*, International Energy Agency, Paris.

IEA: 2004, *World Energy Outlook 2004*. International Energy Agency, Paris.

IIASA: 2001, *http://www.iiasa.ac.at/Research/POP/proj01/index.html*. International Institute for Applied System Analysis, 15-7-2004.

IMAGE-team: 2001, *The IMAGE 2.2 Implementation of the IPCC SRES Scenarios. A Comprehensive Analysis of Emissions, Climate Change and Impacts in the 21st Century.* Netherlands Environmental Assessment Agency (MNP).

Kainuma, M., Matsuoka, Y., Hibino, G., Shimada, K., Ishii, H., Matsui, S., and Morita, T.: 2003, 'Application of AIM/Enduse Model to Japan', in *Climate Policy Assessment - Asia-Pacific Integrated Modeling*, M. Kainuma, Y. Matsuoka and T. Morita. Springer, Tokyo.

Lutz, W., Sanderson, W., and Scherbov, S.: 2001, 'The End of world population growth', *Nature* **412**, 543–545.

Lutz, W., Sanderson, W., Scherbov , S., and Goujon, A.: 1996, 'World population scenarios for the 21st century', in *The Future Population of the World. What Can We Assume Today?* W. Lutz. Earthscan, London: 361–396.

Lutz, W., Sanderson, W. C., and Scherbov, S.: 2004, *The End of World Population Growth in the 21th Century. New Challenges for Human Capital Formation and Sustainable Development*, Earthscan, London.

Manne, A. and Richels, R.: 2003, *Market Exchange Rates or Purchasing Power Parity: Does the Choice Make a Difference in the Climate Debate*, Working paper 03–11. AEI-Brookings Joint Centre for Regulatory Studies.

Marland, G., Boden, T. A., and Andres, R. J.: 2004, *Global, Regional, and National Fossil Fuel CO2 Emissions*, Carbon Dioxide Information Analysis Center – Oak Ridge National Laboratory.

McCathy, J. J., Canziani, O. F., Leary, N. A., Dokken, D. J., and White, K. S.: 2001, *Climate change 2001: Impacts, Adaptation, and Vulnerability*, Cambridge University Press, Cambridge.

McKibbin, W. J., Peace, D., and Stegman, A.: 2004, *Long-Run Projections for Climate Change Scenarios*, Lowy Institute, Sydney.

Metz, B., Davidson, O., Swart, R., and Pan, J.: 2001, *Climate Change 2001: Mitigation*, Cambridge University Press, Cambridge.

Nakicenovic: 2000. *Special Report on Emissions Scenarios (SRES)*. Cambridge University Press, Cambridge, UK.

Nakicenovic, N., Grübler, A., Gaffin, S., Jung, T. T., Kram, T., Morita, T., Pitcher, H., Riahi, K., Schlessinger, M., Shukla, P. R., Van Vuuren, D. P., Davis, G. Michaelis, L., Swart, R., and Victor, N.: 2003, 'IPCC SRES revisited: A response.' *Energy & Environment* **14**(2–3), 187–214.

Nordhaus, W. D.: 2005, 'Alternative measures of output in global economic-environmental models: Purchaisng power parity or market exchange rates?' IPCC Expert Meeting on Emissions Scenarios, Washington DC. IPCC Technical Support Unit WG-III.

Olivier, J. G. J.: 2004, *EDGAR 3: Uncertainties*. Netherlands Environmental Assessment Agency (MNP), Bilthoven.

Olivier, J. G. J. and Berdowski, J. J. M.: 2001, 'Global emissions sources and sinks', in *The Climate System*. J. Berdowski, R. Guicherit and B. J. Heij. A. A. Balkema Publishers/Swets & Zeitlinger Publishers, Lisse, The Netherlands.

Olivier, J. G. J. and Peters, J. A. H. W.: 2002, 'Uncertainties in global, regional and national emission inventories'. Non-CO2 greenhouse gases: Scientific understanding, control options and policy aspects. Proceedings of the Third International Symposium, Maastricht.

O'Neill, B. C.: 2004, 'Conditional probabilistic population projections: An application to climate change', *International Statistical Review* **72**(2), 167–184.

O'Neill, B. C., Balk, D., Brickman, M., and Ezra, M.: 2001, 'A guide to global population projections', *Demographic Research,* **4**(8), 203–288.

O'Neill, B. C. and Desai, M.: 2004, 'The historical accuracy of projections of U.S. energy consumption', *Energy Policy* **33**(8), 979–993.

Richels, R. G., Manne A. S., and Wigley, T. M. L.: 2004, *Moving Beyond Concentrations: The Challange of Limiting Temperature Change*, AEI-Brooking Joint Center for regulatory studies.

Scheele, E. A. and Kruger, D.: 2006, 'Global antropogenic methane and nitrous oxide emissions', *Energy Journal* (Accepted for publication).

Shlyakhter, A. I.,Kammen, D. M., Broido, C. L., and Wilson, R.: 1994, 'Quantifying the credibility of energy projections from trends in past data', *Energy Policy,* **2**, 119–130.

Smil, V.: 2000, 'Perils of long-range energy forecasting: Reflections on looking far ahead', *Technological Forecasting and Social Change* **65**, 251–264.

Smith, S. J., Andres, R. J., Conception, E., and Lurz, J.: 2004a, *Historical Sulphur Dioxide Emissions: 1850–2000: Methods and Results*, PNNL, Washington D.C.

Smith, S. J., Pitcher, H., and Wigley, T. M. L.: 2004b, 'Future sulphur dioxide emissions', *Climatic Change,* (Accepted).

Stern, D. I.: 2003, *Global Sulfur Emissions in the 1990s*. Renselaer Polytechnic Institute, Troy.

Timmer, H.: 2005, 'PPP vs. MER: A view from the World Bank'. IPCC Expert Meeting on Emission Scenarios, Washington D.C., IPCC Technical Support Unit WG-III.

UN: 1998. *World Population Projections to 2150*. United Nations, New York.

United Nations, Department of Economic and Social Affairs, Population Division, 2005, *World Population Prospects: The 2004 Revision. CD-ROM Edition – Extended Dataset* (United Nations publications, Sales No. E.05.XIII.12).

UNEP: 2002. *Global Environment Outlook 3*. EarthScan, London.

US.BoC: 2005, *International Database – Updated 26 April 2005*, US.Bureau of the Census. accessed 16 December 2003.

US.DoE: 2003, *International Energy Outlook*, US Department of Energy – Energy Information Administration, Washington D.C.

US.DoE: 2004a, *International Energy Outlook*, US Department of Energy – Energy Information Administration, Washington D.C.

US.DoE: 2004b, *Total Carbon Dioxide Emissions from the Consumption of Petroleum, Natural Gas, Coal, and the Flaring of Natural Gas, All Countries, 1980–2002*, US Department of Energy – Energy Information Administration, Washington DC.

Van Vuuren, D. P., Fengqi, Z., De Vries, B., Kejun, J., Graveland, C., and Yun, L.: 2003, 'Energy and emission scenarios for China in the 21st century – exploration of baseline development and mitigation options', *Energy Policy* **31**, 369–387.

Webster, M. D., Babiker, M. H., Mayer, M., Reilly, J. M., Harnisch, J., Hyman, R., Sarofim, M. C., and Wang, C.: 2002, 'Uncertainty in emissions projections for climate models', *Atmospheric Environment* **36**(22), 3659–3670.

Weyant, J. P., De la Chesnaye, F. C., and B. G.: 2006, 'Overview of EMF – 21: Multigas Mitigation and Climate Change', *Energy Journal* (Accepted for publication).

World Bank: 2004, *World Economic Prospects 2004*, Worldbank, Washington DC.

World Bank: 2005, *World Development Indicators* - CD-ROM.

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