

3. THE CONSISTENCY OF THE IPCC SRES SCENARIOS CONSISTENT WITH RECENT LITERATURE AND RECENT PROJECTIONS

Abstract. The greenhouse gas emissions scenarios published by the IPCC in the *Special Report on Emission Scenarios (SRES)* continue to serve as the primary basis for assessing future climate change and possible response strategies. These scenarios were developed between 1996 and 1999; sufficient time has now passed to make it worthwhile to examine their consistency with more recent data and projections. Population, GDP, energy use, and emissions of CO₂, non-CO₂ gases and SO₂ are compared in this chapter. Findings revealed that the SRES scenarios are largely consistent with historic data for the 1990–2000 period and with recent projections. Exceptions to this general observation include: (1) population growth assumptions in SRES in some regions, particularly in the A2 scenario, which are relatively high compared to new scenarios (long term); (2), economic growth assumptions in the ALM (Africa, Latin America and Middle East) region in the A1 scenario, which are relatively high compared to recent projections (medium-term); (3) CO₂ emissions projections in A1 that are somewhat higher than the range of current scenarios (short term); and (4) SO₂ emissions in some scenarios that are substantially higher than in historic 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.

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3.1 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 and Swart, 2000). The SRES scenarios were developed in a relatively open process that started in 1996. Six modeling teams participated officially in the exercise to develop new scenarios.ⁱ

The IPCC scenarios cover very long time periods (1990–2100) so as to capture the large inertia present 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

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

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

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 new modeling was often consistent with the overall SRES storylines and published parameters (UNEP, 2002; de Mooij and Tang, 2003; Kainuma et al., 2003; van Vuuren et al., 2003c).

At the same time, several criticisms of the SRES scenarios have been made, mainly outside of the peer-reviewed literature (Economist, 2003b; Economist, 2003a). 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 historic 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 historic emission trends (e.g. Corcoran, 2002). Apart from 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 showed rapid 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 projections that could affect future trends. Such outlooks often focus on shorter time frames than SRES (20–30 years rather than 100 years). In some cases, however, new long-term scenarios have been published.

Here, 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, 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 3.2 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 3.3 and emissions in Section 3.4. Conclusions are presented in Section 3.5.

3.2 Methodology

We focused our assessment on the SRES scenarios as published by IPCC (Nakicenovic and Swart, 2000).ⁱⁱ Box 3.1 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 modeling 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 CO₂, other greenhouse gases and SO₂. Comparison was done at the level of aggregation reported by SRES – 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

ⁱⁱ 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 it is 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.

and Middle East (ALM).ⁱⁱⁱ Three types of comparisons were made, namely, comparison to : 1) data covering the (by now) historic 1990–2000 period, 2) short-term projections published since 2000 and 3) long-term projections published since 2000. The projections used in our comparison have been selected on the basis of their recent publication dates and the fact that they are often used as reference projections within their specific domains. In addition, we excluded 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.

Box 3.1 Terminology from the IPCC SRES scenarios

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” and “2”, respectively) and 2) the emphasis on economic development versus social and environmental factors (these scenarios are marked as “A” and “B”, respectively). Combining these axes results in the four scenario families, named A1, A2, B1 and B2, alluding to the underlying fundamental assumptions: In addition, two other scenario storylines (termed “illustrative scenarios”) result from different technology assumptions within the A1 family. For each storyline, there are several quantitative scenarios produced by different modeling 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 were 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. 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 was to evaluate the SRES scenarios as they are published, and normally used (and not to evaluate the performance of the underlying models), we 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 historic data. In contrast, the data for driving forces has not been standardized and individual model results and assumptions cannot be compared to historic trends.

Based on (Nakicenovic and Swart, 2000)

In theory, a fourth comparison might 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 driv-

ⁱⁱⁱ As indicated in the SRES report, the different regional breakdown of the different models did not always allow for consistent aggregation into the IPCC regions. In these cases, slightly different regional 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.

ing 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 (SO₂ 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, 2004b) and with the US Department of Energy's International Energy Outlook (US.DoE, 2004b) (both report on GDP, energy use and CO₂ emissions), and the results of the model comparison study done by the Energy Modelling Forum (EMF-21) (Weyant et al., 2006). We used the so-called "modeler's reference scenario" from the last study which are usually "medium-growth" scenarios. In total, available data from this study included long-term data for 14 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, this 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 US 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 used selected modelling studies. It should be noted that the historic data can be accompanied by considerable levels of uncertainty. 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).

3.2.1 Assumptions underlying the IPCC scenarios

The main assumptions underlying the four scenario families (A1, A2, B1 and B2) are indicated in Table 3.1. 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 this does not mean that the four families represent all possible outcomes or a representative sample across the possible outcomes. In fact, the assumed trends for drivers include (see also Table 3.1):

- 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).

Table 3.1 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

3.2.2 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 one a sense of 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 can 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 sensitiv-

ity analysis, but includes no characterization by the authors of the likelihood of the outcome. The UN population projections form 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, 2004b). 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 boundary of such projections, even over relatively short time horizons (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 CO₂ 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 potential methodological differences in mind when developing longer vs. shorter term outlooks. The modeling 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 on why consistency between long-term scenarios (like SRES) and short-term historic trends and outlooks is relevant:

1. If inconsistency with historic 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 this is important information for potential users.
3. An insufficient match between SRES and short-term trends or historic 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 modeling 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 modeling (a hundred-year time frame or more), only the first and third arguments apply. It should also be noted that because climate modeling 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 historic data, short-term outlooks or long-term scenarios. Our judgment on reasonableness take into account that (a) a good performance on trends is more essential than an exact reproduction of specific results for any given year and that (b) historic data also show some uncertainty, so that “matching” such data is to some extent a statistical concept.

3.3 Results for Main Driving Forces

3.3.1 Population

3.3.1.1. *Historic 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 (A1/B1 and B2) (Lutz et al., 2001). Both of these projections used the base year of 1990. As shown in Table 3.2, 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 historic population estimates undergo regular 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 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 historic trends in population size.

Table 3.2 Comparison of SRES population trends with 1990-2000 data (in millions)

		UN data	A1/B1	A2	B2
OECD	1990	866	864	864	863
	2000	929	919	923	916
	Ratio	1.07	1.06	1.07	1.06
EIT	1990	412	412	412	412
	2000	411	419	421	415
	Ratio	1.00	1.02	1.02	1.01
Asia	1990	2791	2807	2807	2788
	2000	3245	3260	3295	3248
	Ratio	1.16	1.16	1.17	1.16
ALM	1990	1195	1200	1200	1188
	2000	1484	1519	1530	1510
	Ratio	1.24	1.27	1.28	1.27
World	1990	5264	5282	5282	5251
	2000	6069	6117	6171	6089
	Ratio	1.15	1.16	1.17	1.16

Source: (UN, 2003).

3.3.1.2. Recent Projections for the Medium Term (up to 2050)

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).

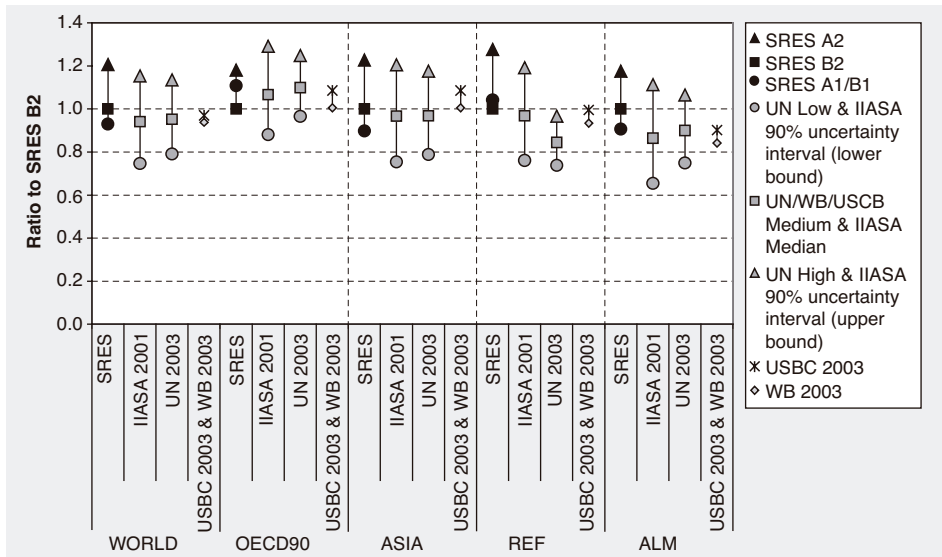
Updated projections, however, generally anticipate less global population growth than the projections used in the SRES scenarios. Since the early 1990s, birthrates in many parts of the world have fallen surprisingly fast and the AIDS epidemic has taken an unexpectedly large toll. These changes have led demographers to revise their outlook on future population size downward, toward smaller, older populations than previously anticipated. For example, Figure 3.1a compares the projections for 2050 used in SRES to the most recent IIASA (Lutz et al., 2001; Lutz et al., 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 3.1a 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, some changes can be noted. First of all, there is a small downward revision to the medium (or “best guess”) projections. Second, small downward revisions also occur at the high end of the uncertainty range. Finally, a relatively large downward revision can be noted 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 downwards, so that the SRES A2 scenario now no longer falls within the 90% uncertainty interval; it now lies 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 lies 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.

(a)



(b)

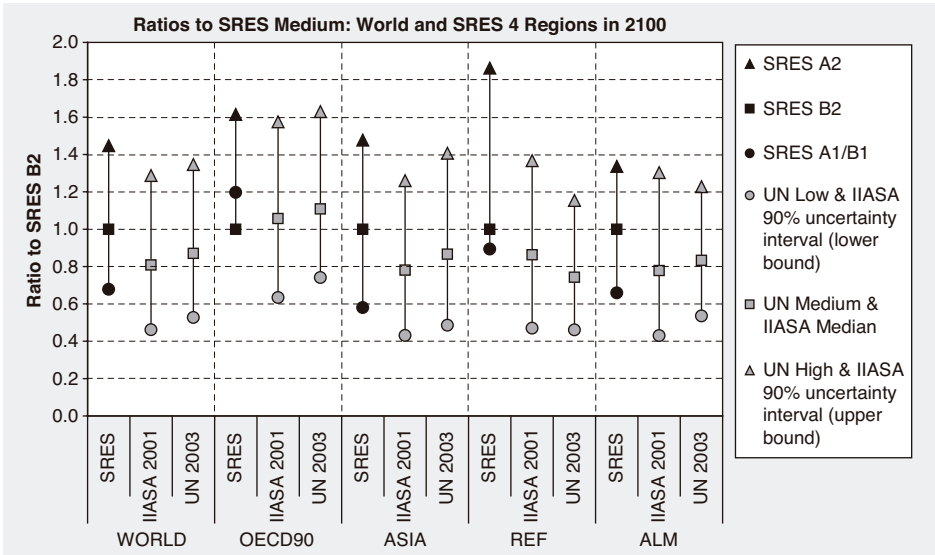


Figure 3.1 Population size worldwide and for four SRES macro regions relative to the population size in the SRES B2 projection for (a) 2050 and (b) 2100. Source: (Nakicenovic and Swart, 2000; Lutz et al., 2001; UN, 2003; US.BoC, 2003; WorldBank, 2005).

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 on 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, while updated IIASA assume 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.

3.3.1.3. 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 3.1b. 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. Just as for 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.

3.3.1.4. Credibility of SRES Assumptions

Although the range of projected population sizes has shifted downwards 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 3.1). What is clearly missing, however, in the 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 (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 lies 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. All else being equal, lower population growth projections are likely to lead to lower

emissions levels (however, there are dynamic feedbacks such as lower fossil fuel consumption leading to less depletion, thus lower prices). This could, in turn, partly offset fuel reduction).

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.

3.3.2 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 other aspects, in exchange rates and the influence of base year. The World Bank (2005), the main source of historic 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 of underlying data by the Bank. For growth rates, however, the impact of base year is much smaller.^{iv} Therefore, we will focus on growth rates rather than the absolute numbers (see Table 3.3 for world data and the 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

^{iv} 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.

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 has not yet ended. 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 on 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 a means to aggregate the real drivers of emissions, i.e. physical activities. In addition to the aggregated drivers, 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 (2005) showed that in their simple model consistent replacement of the metric for economic activities expressed in monetary terms (PPP for MER) throughout the model (i.e. 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. This then 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 in studies that report in PPP values (IEA, for instance), their growth rates were first assigned to MER income estimates on a regional basis in the base year.

3.3.2.1. Historic Trends

The historic data used (WorldBank, 2005) indicates an overall 13% growth between 1990 and 2000 in per capita GDP.^v In general, there is a reasonable agreement with the data reported for the four SRES scenarios and the historic 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 markers 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 historic data. Finally, the A2 scenario shows too low growth rates in the OECD. But overall, it can be concluded that the SRES scenarios have captured the direction and the relative magnitudes of growth rates across the four regions reasonably well (Table 3.3).

Table 3.3 Comparison of SRES per capita GDP trends with 1990-2000 data (in US\$ per capita)

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

Source: (Nakicenovic and Swart, 2000; WorldBank, 2005).

^v 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.

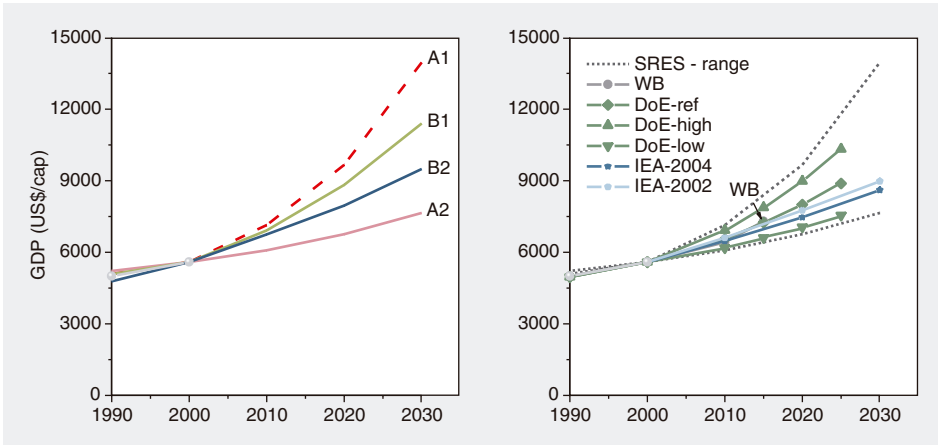


Figure 3.2 Comparison of global GDP growth in the SRES scenarios and more recent projections. SRES = (Nakicenovic and Swart, 2000), WB = World Bank (WorldBank, 2004), DoE = assumptions used by US Department of Energy (US.DoE, 2004b), IEA assumptions used by IEA (IEA, 2002; IEA, 2004b).

Note: In order to allow comparison, reported regional growth rates for all studies were used on the basis of World Bank data (in market exchange rate 1995 US\$) for base year (2000).

3.3.2.2. Recent Projection for the Medium Term (up to 2050)

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 3.2). In the 2004 version, the economic scenarios of IEA's World Energy Outlook are based on OECD, World Bank and IMF 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 country base developed by Global Insight, Inc. (2003), except for 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^{vi}.

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, the 2000–2010 per capita growth

^{vi} In other words, economic projections are in all these studies exogenous inputs into the energy projections – and there is no dynamic link between the two.

rate in the group of low-income countries 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 the 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, 2004b).

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, 2004b). 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 on the regional scale (Figure 3.3). 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

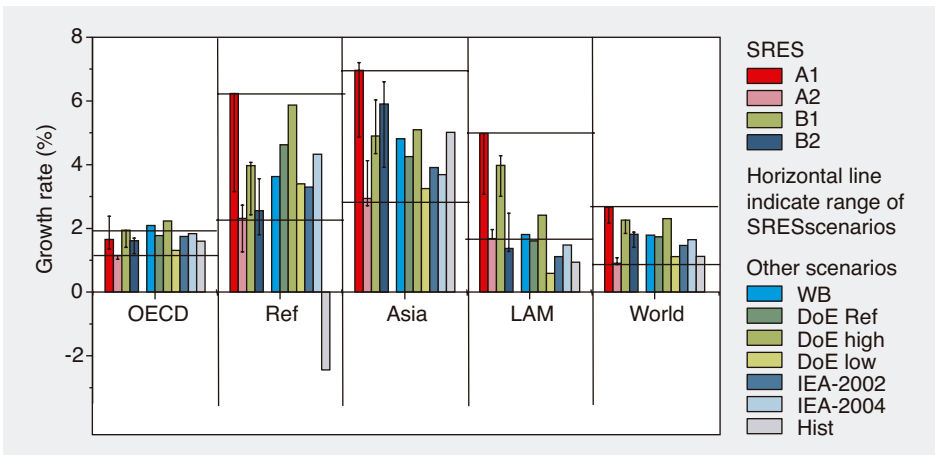


Figure 3.3 Comparison of the regional annual average growth rate of per capita GDP between 2000-2015 in the SRES scenarios and more recent studies. WB = (WorldBank, 2004), DoE = Reference, high and low scenario of US.DoE (2004b), IEA = International Energy Agency (IEA, 2002; IEA, 2004b). Hist = Historic data from World Bank (WorldBank, 2005). 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 historic rate represents the 1990-2000 period.

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 lie 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%.

Again, the A1 and B1 storyline 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 both the A1 and B1 scenarios 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 and Swart, 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 these regions will not yet experience an economic take-off similar to what the East Asian economies achieved over the past two decades (WorldBank, 2005).

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 lie 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 being fairly optimistic. On a global scale, this means that A1 is somewhat outside the range of current projections.

3.3.2.3. 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 modeling 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 are not intended to explore the upper or lower range of possible growth rates. Richels et al. (2004) published long-term economic projections with uncertainty ranges. Figure 3.4 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.

3.3.2.4. 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

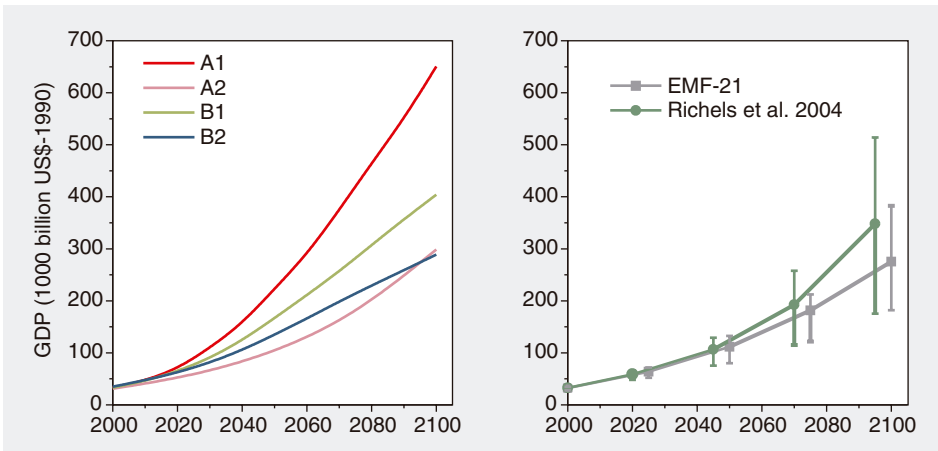


Figure 3.4 Comparison of the SRES scenarios with the range of GDP projections used in recent long-term scenario studies. The range in EMF-21 (Weyant et al., 2006) indicates the lowest and highest projections included in a set of baseline projections of different models. The range for Richels et al. (2004) represents the 5th and 95th percentiles of the distribution in that study.

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 the ALM region might only be a problem in using the SRES scenarios for this specific region. One may question whether SRES researchers have appreciated enough that long-term storylines, particularly in the ALM region need to overcome important inertia. 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.

3.3.3 Energy use

3.3.3.1. *Historic 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 3.4). It should be noted 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.^{vii} 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 historic 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 low 2000 energy use for the FSU, and A1's lower and A2's higher 1990-2000 increase for Asia.

3.3.3.2. *Recent Projections for the Medium Term (up to 2050)*

Figure 3.5 shows that the range covered by the set of near-term projections nearly captures that of SRES, and that the projections from IEA's World Energy Outlook (IEA, 2002; IEA, 2004b) and US.DoE's central projection (US.DoE, 2004b) are near the SRES median.^{viii} 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 CO₂ emissions, regional trends are discussed only for the latter.

3.3.3.3. *Credibility of SRES Assumptions*

The results for energy are consistent with our earlier findings for GDP assumptions in SRES. SRES reflects historic trends reasonably well, and compares well on a global scale with near-term projections in recent studies. The energy use in the A1 marker

^{vii} The A2 marker scenario was developed by the ASF modeling team. This model does not calculate traditional biomass numbers; A2 elaborations of other modeling teams do include traditional biofuel projections.

^{viii} For a description of the differences between the reference, low and high projections of US.DoE see the section on GDP growth.

Table 3.4 Comparison of SRES trends in primary energy use with 1990-2000 data (in EJ)

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

Source: (Nakicenovic and Swart, 2000; IEA, 2003b)

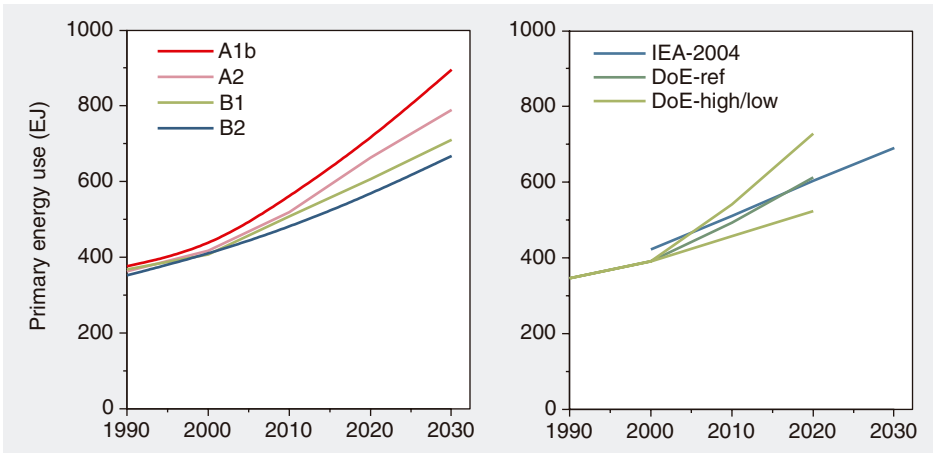


Figure 3.5 Comparison of trends in SRES total primary energy consumption with more recent studies by US DoE and IEA. DoE = Projections from US DoE (2004b), IEA-2004 = Projection from the International Energy Agency. (IEA, 2004b). Note: Original A2 scenario as reported in SRES does not contain non-commercial biomass use. Therefore for A2 biomass data has been taken from IEA energy data – and held constant after 2000.

scenario lies somewhat above the range of near-term projections and therefore might be considered somewhat less likely than other scenario outcomes, 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.

3.4 Results for Emission Projections

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

3.4.1 CO₂ emissions from energy and industry

3.4.1.1. Historic 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 CO₂ emissions in the year 1990 (compared to a standardized value of 7.1 GtC retained for the SRES scenarios) (Nakicenovic and Swart, 2000). By far the largest part of this uncertainty range is attributable to emissions from land-use change, although for industrial sources of CO₂ 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 CO₂ emissions come from differences in coverage (cement manufacturing, bunker emissions and feedstocks are often 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 CO₂ 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 3.5).

Table 3.5 illustrates the uncertainties in past and current emission estimates by showing the difference between the various inventories. Of these sources, IEA and EDGAR

Table 3.5 Emission inventories of industrial CO₂ 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 MtCO₂, 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 and Swart, 2000; Olivier and Berndowski, 2001; IEA, 2003a; Marland et al., 2004; US.DoE, 2004a)

are the most detailed^{ix}. 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 CO₂ increase in this region in SRES results from expectations in the late 1990s that Chinese emissions would continue to grow rapidly. In reality, emission growth in China has probably been relatively slow in the second half of the 1990s. However, development of Chinese CO₂ emissions during this period has been subject to debate. In the early 2000s, some data sources (e.g. CDIAC) indicated a decline in Chinese emissions in the late 1990s, caused by both a slowdown 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., 2003c). Since then historic 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 CO₂ 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.

3.4.1.2. Recent Projections for the Medium Term (up to 2050)

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 3.6). These scenarios (called the “modeler’s preference baseline”) represent “medium”-growth scenarios, and the range should be interpreted as an indication of how different modeling groups, using different models, assess the range of such medium projections.^x 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

^{ix} There are still considerable differences between the different inventories, despite our attempts to harmonize the coverage. For most inventories the differences are consistent with the uncertainty estimate for the EDGAR CO₂ emission inventory. Differences may result from calculation methods, detail and emission factors used.

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

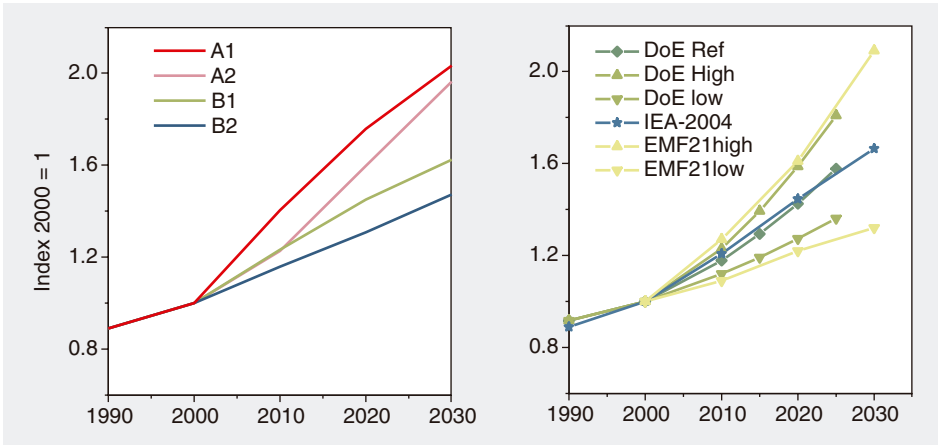


Figure 3.6 Comparison of trends in global CO₂ emissions, SRES versus more recent projections. DoE = Projections from US. DoE (2004b), IEA = Projection from the International Energy Agency. (IEA, 2004b). EMF-21 indicates the range of the lowest and highest reported values in the EMF-21 study (Weyant et al., 2006).

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 3.7). For the OECD region, emission increases in the 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.

3.4.1.3. Long-Term Projections

As in the case of GDP, there are no official institutions publishing long-term CO₂ emission scenarios independent of SRES. Instead we use scenarios from individual modeling groups (Figure 3.8), taken from the EMF-21 set (Weyant et al., 2006) (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 modeling teams. Taken collectively, the set of SRES scenarios lies somewhat below the EMF-21 set – with the B1 scenario standing out as

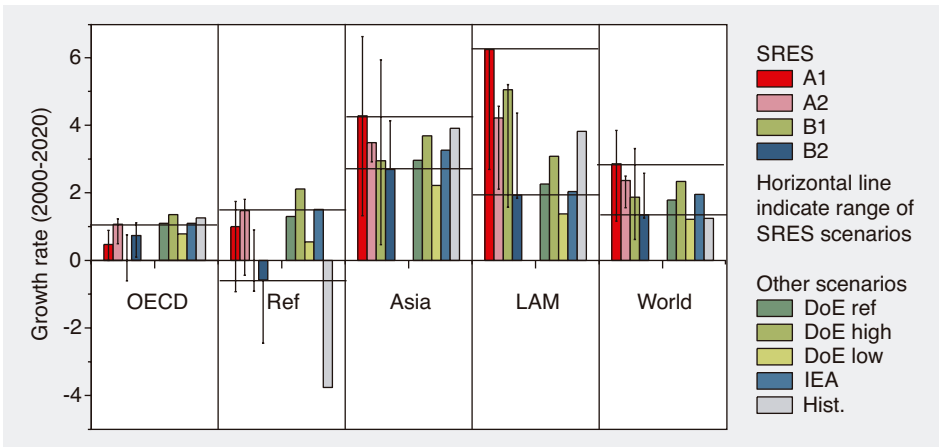


Figure 3.7 Comparison of trends in regional CO₂ emissions, SRES versus more recent projections (2000-2020 annual average growth rates). DoE = Projections from US. DoE (2004b). IEA = Projection from the International Energy Agency (IEA, 2004b). Hist = Historic data from the IEA energy database. The horizontal 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 historic rate represents the 1990-2000 period.

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 those for climate). The comparison with the set of probabilistic projections shows a similar result: the SRES scenarios cover a similar range, with the mean and range of the SRES set somewhat below the range of other two other studies.

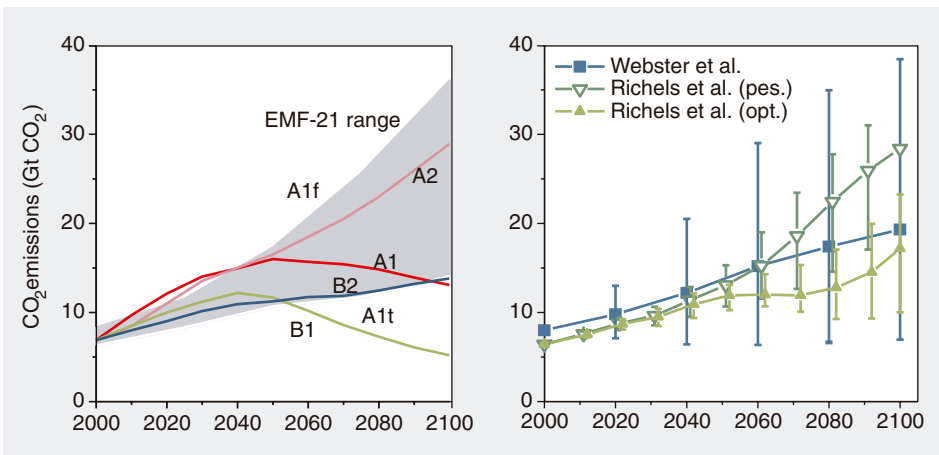


Figure 3.8 Comparison of the SRES scenarios to recent long-term scenarios for CO₂ emissions. EMF-21 indicates the range of the lowest and highest reported values in the EMF-21 study (Weyant et al., 2006). Webster et al. (2002) and Richels et al. (2004) indicate the mean and reported ranges of these studies.

3.4.1.4. *Credibility of SRES Assumptions*

For CO₂, the comparison of the SRES scenarios with more recent information shows that the SRES scenarios are generally consistent with historic 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 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.

3.4.2 Non-CO₂ greenhouse gases

3.4.2.1. *Historic Trends*

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

Worldwide, methane emissions were 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 historic estimate cannot be taken as statistically significant. For N₂O, 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.^{xi} The uncertainty in N₂O emission inventories is considered to be substantially larger than for CH₄, 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 emission inventories for these gases. However, uncertainty levels in the EDGAR database (Olivier, 2004) are still assessed to be about 50–100 %.

^{xi} 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.

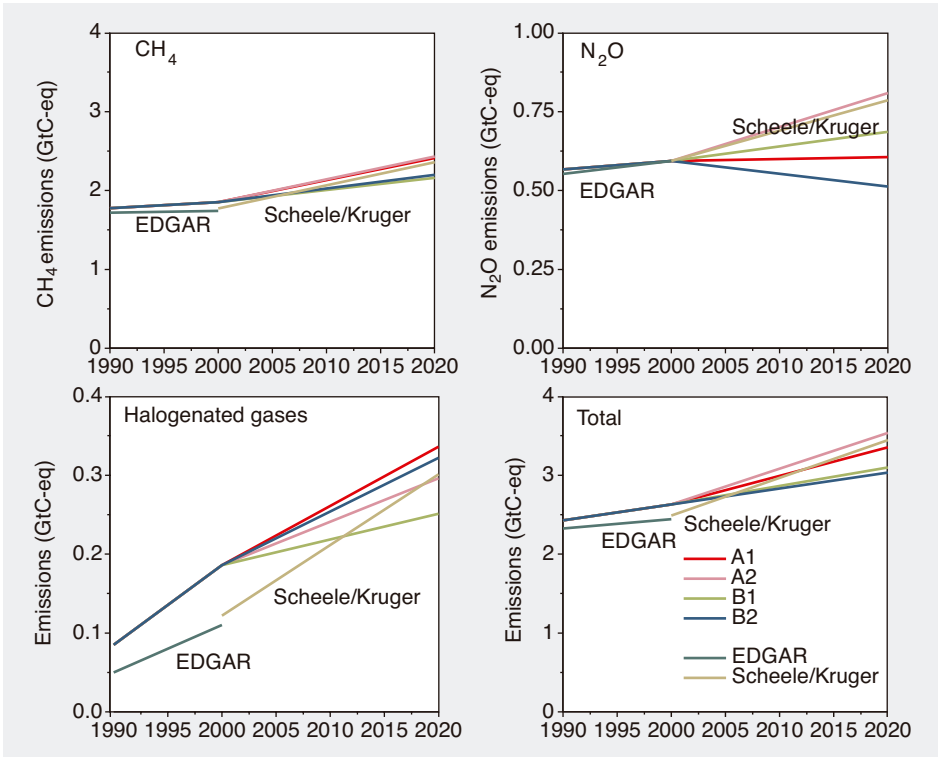


Figure 3.9 Comparison of trends in global non- CO_2 emissions, SRES, versus more recent projections. EDGAR indicates the historic data included in the EDGAR database (Olivier and Berndowski, 2001), Scheele/Kruger indicates the projections of Scheele and Kruger (2006).

3.4.2.2. Recent Projections for the Medium Term (up to 2050)

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 3.9 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, SF_6 and PFCs.

3.4.2.3. Long-Term Projections

In the context of EMF-21 a major modeling effort was made to update the capability of long-term integrated assessment models for modeling 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) represent agricultural drivers in more detail. We have used all model outcomes of EMF21 as an indication of the range of model

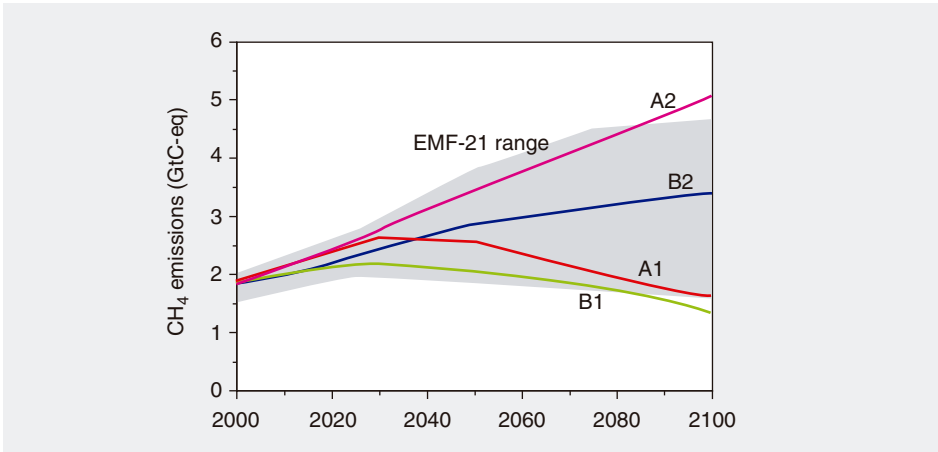


Figure 3.10 Long-term trends in methane emissions, SRES versus more recent projections (EMF-21). EMF-21 indicates the range of the lowest and highest reported values in the EMF-21 study (Weyant et al., 2006).

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).

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 3.10). In general, methane and nitrous oxide in both SRES and EMF-21 display somewhat slower growth rates than CO₂ emissions as these emissions are coupled, in particular, with agricultural drivers – which show lower growth rates than energy drivers (important for CO₂).

3.4.2.4. Credibility of SRES Assumptions

The SRES scenarios seem to be fully in line with more recent projections for the non-CO₂ greenhouse gases.

3.4.3 Sulfur-oxide emissions (SO₂)

3.4.3.1. Historic Trends

Aerosols from SO₂ emissions can have a significant cooling effect and therefore form an important element of the SRES scenarios. Table 3.6 shows the 1990–2000 SO₂ data according to three different estimates (Amann, 2002; Stern, 2003; Smith et al., 2004) in comparison to the assumptions included in SRES. It should be noted that here again, there is considerable uncertainty involved in SO₂ 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 CO₂, 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 3.6 Emission trends for sulfur emissions 1990-2000 (in Tg S)

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

In SRES, worldwide SO₂ 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 portion 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. (2004) and Stern (2003).

3.4.3.2. Recent Projections for the Medium Term

The SRES scenarios can be compared to more recent near-term projections of Amann (2002) and Smith (2005). The projections of Amann (up to 2020) were made on the basis of existing country-level projections and reduction plans,^{xii} but did not include all countries. Therefore, the data set was extended to the global level using 2000 emission levels from Stern (2003), assuming similar growth rates as for the regions for which data was directly available. The work of Smith (2005) 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 and since the modelers have paid much more attention to the trends in SO₂ emissions, the study can be regarded as an independent source.

^{xii} Amann's inventory included the OECD, REF and the Asia regions. 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.

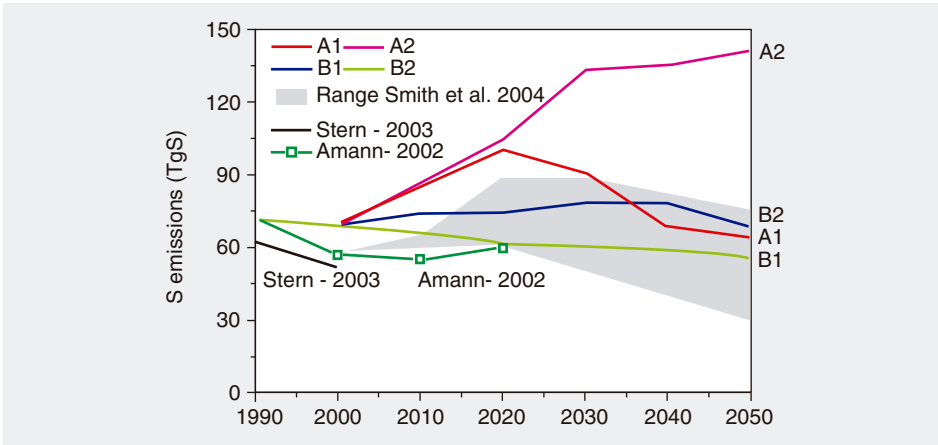


Figure 3.11 Comparison of SRES sulfur emissions and more recent projections. Data based on (Amann, 2002; Stern, 2003; Smith et al., 2004).

The comparison (Figure 3.11) shows the highest of the SRES projections to be apparently very high (this certainly holds for A2 and for the first 20 years of A1) and as a consequence rather unlikely. Furthermore, the lower range of the scenarios has shifted 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 SO_2 emissions might not increase as rapidly as a result of desulfurization policies in low-income countries is in fact relatively recent. It is interesting to note that during the review procedure, the SRES scenarios were actually criticized for including too low SO_2 emission scenarios. Compared to all other variables then, the degree of inconsistency of SRES with both historic emission trends and near-term expectations is highest for SO_2 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.

3.5 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 3.7.

- **In almost all the cases of (now) historic development, the SRES assumptions for 1990 and 2000 are reasonably consistent with available data, but there are some exceptions.** 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

Table 3.7 Main inconsistencies found between the SRES scenarios and more recent scenarios and data

<i>Parameter</i>	<i>Inconsistencies noted in comparison</i>
Population	<ul style="list-style-type: none"> • SRES does not include a representation of the current low-end population scenarios • The A2 scenarios outside the current 95% probability estimate • For specific regions (in particular sub-Sahara Africa and China), differences between SRES and current projections larger
GDP	<ul style="list-style-type: none"> • Global economic projection for A1 outside range of current projections in the first two decades • The set of SRES scenarios for the ALM region seemingly representative of the upper end scenarios only
Energy	<ul style="list-style-type: none"> • See GDP
CO ₂	<ul style="list-style-type: none"> • See GDP for short-term projections • Slightly too high for 2000 emissions
Non-CO ₂ gases	<ul style="list-style-type: none"> • Historically seen, somewhat too high for the F gases • Several forcing agents (black carbon) not yet included
Sulfur	<ul style="list-style-type: none"> • 2000 sulfur emissions too high. • Emissions in the first decades of the high emission scenarios unlikely

small (mostly caused by the decline in coal use in the late 1990s in China). Finally, for SO₂ 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 CO₂ and SO₂ 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 still fall in most cases within the range of new literature, in a few they go beyond the literature. 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 is 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) to be magnified in the long term (2100) due to the path dependency of population growth. Lower population pathways, all else being 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 (income, energy use and CO₂ emissions).** Here, the range of SRES economic growth assumptions and resulting growth rates for energy use and CO₂ 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 emission 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 is seen for SO₂.** 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 SO₂ emissions, as in some of the SRES scenarios for SO₂ 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 SO₂ emissions. Other factors being equal, such a revision would imply an increase in the expected short-term temperature change associated with the SRES scenarios.
- **There are a few elements such as black and organic carbon and grid-based land-use projections that have not been included in the SRES scenarios in much detail and which recently have become much more important for climate change projections.** Non-official projections consistent with SRES assumptions have now become available from individual modeling teams.
- **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 modeling groups could decide to update their scenarios.** 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. Individual modeling groups could nevertheless 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 that scenarios would have 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 (as in IPCC’s Fourth Assessment Report, for instance). 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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