EMISSIONS SCENARIOS DATABASE AND REVIEW OF SCENARIOS

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Abstract. This paper reviews and analyzes more than 400 scenarios of global and regional greenhouse gas emissions and their main driving forces – population, economy, energy intensity, and carbon intensity – drawn from an extensive literature survey and summarized in a database. This new and growing database is available online, which makes summary statistics on these scenarios widely available. The scenarios in the database were collected from almost 200 different literature sources and other scenario evaluation activities. The ultimate objective of the database is to include all relevant global and regional emissions scenarios. This paper shows how the database can be utilized for the analysis of greenhouse gas emissions ranges across the scenarios in the literature and for the analysis of their main driving forces. The scenarios in the database display a large range of future greenhouse gas emissions. Part of the range can be attributed to the different methods and models used to formulate the scenarios, which include simple spreadsheet models, macroeconomic models and systems-engineering models. However, most of the range is due to differences in the input assumptions for the scenarios, in particular of the main scenario driving forces. Special emphasis is given to an analysis of medians and ranges of scenario distributions and the distributions of the main scenario driving forces in the database. The analysis shows that the range for projected population increase in the world, across the scenarios in the database, is the smallest of all main driving forces (about a factor of 3 in 2100). The range of economic growth, measured by the gross world product, and the range of primary energy consumption vary by a factor of 10 in 2100. Carbon intensity of energy, an indicator of the degree of technological change, varies by nearly two orders of magnitude in the year 2100. In addition, this paper presents the first attempt to analyze the relationships among the main scenario driving forces. Subsequent papers in this special issue give further analyses of the relationships among the main scenario driving forces and their other relevant characteristics.

Key words: carbon dioxide emissions, carbon intensity, decarbonization, emissions scenarios, energy intensity, global and regional scenarios, greenhouse gas emissions, review of scenarios, scenario database.

1. Introduction

There is increasing evidence that the anthropogenic sources of greenhouse gas (GHG) emissions may lead to global climate change. GHG emissions scenarios provide an important input for the assessment of future climate change. This paper reviews 428 scenarios of global and regional GHG emissions drawn from an extensive literature survey and summarized in a database. Future GHG emissions depend on a number of driving forces such as global population

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growth, economic development and energy supply. The main driving forces that determine the emissions trajectories in the scenarios often also provide input to the assessment of possible emission mitigation strategies and possible impacts of unabated emissions. It is therefore not surprising that there are numerous emissions scenarios in the literature and that the number of scenarios of regional and global emissions is growing by the day.

The scenarios in the database were collected from 176 different literature sources and other scenario evaluation activities such as the Energy Modeling Forum (EMF, see Weyant, 1993) and the International Energy Workshop (IEW, see Manne and Schrattenholzer, 1996, 1997). The ultimate objective of the database is to include all relevant global and regional emissions scenarios. This paper shows how the database can be utilized for the analysis of GHG emissions ranges and their main driving forces.

The scenarios in the database display a large range of future GHG emissions. Part of the range can be attributed to the different methods and models used to formulate the scenarios, which include simple spreadsheet models, macroeconomic models and systems-engineering models. However, most of the range is due to differences in the input assumptions of the scenarios, in particular the differences in the main scenario driving forces. In addition, just comparing alternative emission levels across different scenarios is not sufficient to shed light on internal consistency, plausibility and comparability of the assumptions behind the scenarios; analysis of the underlying driving forces is thus also an important part of the evaluation. Here we analyze the main driving forces such as population growth, economic growth, energy consumption, and energy and carbon intensities. Some of these driving forces are specified as model inputs, and some are derived from model outputs, so we have also attempted to determine the assumed relationships among the main driving forces.

2. Background

In 1990 the Intergovernmental Panel on Climate Change (IPCC) adopted its first set of greenhouse gas emissions scenarios designed to serve as inputs to General Circulation Models (GCMs) and to facilitate the assessment of climate change impacts. Two years later, this first set of scenarios was updated by the six so-called IS92 reference emissions scenarios (Leggett *et al.*, 1992 and Pepper *et al.* 1992). In 1994, the IPCC evaluated the IS92 scenarios (IPCC, 1995).

The IPCC evaluation summarized the following purposes of emissions scenarios: first, to provide input for evaluating climatic and environmental consequences that would occur without specific mitigation measures and policies to reduce emission of greenhouse gases; second, to evaluate climatic and environmental consequences in light of policy interventions directed at reducing future emissions; third, to serve as input in the assessment of mitigation potentials and costs in different regions and economic sectors, and over time; and fourth, to provide input for negotiating possible emissions reductions (Alcamo *et al.*, 1995).

In May 1996, the IPCC decided to develop a new set of reference emissions scenarios as an IPCC Special Report on Emissions Scenarios (SRES). The main objective of the SRES is to review the literature and, based on the outcome, formulate a new set of scenarios to replace the six IPCC IS92 scenarios that are widely used as reference emissions trajectories.

The new set of reference scenarios is intended for use in future IPCC assessments and by the wider community of scientists working on impacts of future greenhouse gas emissions and on mitigation measures and policies. These scenarios should provide the emissions profiles that can be used as inputs to GCMs and other models of climate change. They should also provide the reference information required for assessments of climate change impacts, such as the level of economic activity in different world regions, rates of technological change, and population growth. Such information, in conjunction with emissions trajectories, can also serve as benchmarks for the evaluation of alternative mitigation measures and policies.

In January 1997, the writing team was appointed to formulate a new set of scenarios and the work commenced. The team adopted a work program consisting of four major components: first, a review of existing global and regional emissions scenarios; second, a statistical analysis of the main characteristics and relationships among variables; third, a formulation of narrative "storylines" and quantification of scenario characteristics; and fourth, an "open" scenario modeling process involving feedback from various worldwide modeling groups resulting in the final revisions of the new emissions scenarios. This paper describes progress related to the first two components of the work program.

The first component comprises a unique database that now documents more than 400 global and regional scenarios. This database is accessible at an ftp-site (password and address provided on request). The ultimate objective is to expand the database into a scenario assessment tool in itself and to include as many scenarios as possible. The essential part of the literature review is complete at the time of writing this paper but will be updated throughout the SRES process. This paper briefly describes this database, more detail is given in the Appendix.

The second component—statistical analysis of the scenarios in the database—is well underway. This paper presents the first results—for example, the ranges of main scenario characteristics, such as population, economic development, energy consumption, rates of technological change and GHG emissions. Particular emphasis has been given to an analysis of the medians and the ranges of scenario distributions for each of the salient scenario characteristics, because they will be used in developing the new SRES scenarios, which should reflect the range of values in other published scenarios. In addition, this paper presents the first attempt to analyze the relationships among the main scenario driving forces. Subsequent papers in this special issue give further analyses of the relationships among the main scenario driving forces and their other relevant characteristics.

3. Methodology

The database includes emissions of all GHGs reported for the scenarios. However, most of the emissions scenarios include only energy-related carbon dioxide (CO_2) emissions. Some scenarios include CO_2 emissions due to changes in land-use (e.g., afforestation). Only a few scenarios are available for methane (CH_4), nitrous oxide (N_2O) and other GHGs. Consequently, this paper analyzes only energy-related CO_2 emissions, which is the most important source of anthropogenic global warming.[1] Although we could not include non-CO_2 GHG emissions and non-energy CO_2 emissions, we believe that the results would be similar if they were available. This represents an important area for future work.

We consider individual scenarios as independent entities in the database. Clearly, in practice, individual scenarios are often related to each other and not always developed independently. Some are simply variants of others generated for a particular purpose. Many "new" scenarios are designed to track existing benchmark scenarios. Furthermore, not all scenarios are created equal. Some represent elaborate efforts, which include extensive reviews and revisions; others are simply the outcome of input assumptions. Some are based on extensive formal models, while others are generated with simple spreadsheets, or without any formal tools. Finally, but perhaps most importantly, some scenarios represent futures that assume that certain policies are to be implemented that affect how the future unfolds ("intervention" or "control" scenarios), while others assume no policy-explicit interventions, especially concerning regulation of GHG and other emissions ("non-intervention" or "non-control" scenarios). The borders between all these different types of scenarios are not always easy to identify, and there are many overlapping gray zones. It was not possible to classify the scenarios in the database according to any obvious scheme. Thus, we decided for the purpose of this paper to treat them as statistically independent objects and to compare their relevant attributes. In the analysis we examine both global and regional scenarios.[2]

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[1] For many of the scenarios that include both energy-related and land-use CO_2 emissions it was not possible to separate these two types of emission sources using data available in the database. That explains why some scenarios report negative carbon emissions in the distant future (e.g., Figure 1 of this paper). Further improvements to the database should rectify this situation.

[2] Full details of the regional scenarios are listed in Table A1 in Appendix. It is very difficult to come to any general conclusions for regional comparison, as the ranges involved in regional scenarios are extraordinarily big. Moreover, the number of available scenarios is limited, except for the USA, Europe, the Former Soviet Union (FSU) and China.

Five complementary methods of analysis are used: (1) charts showing the distributions of scenarios along their main characteristics and driving forces, including CO_2 emissions, population growth, global world product (GWP), energy consumption, energy intensity and carbon intensity; (2) histograms, which show the range of values of main scenario driving forces together with associated statistics such as the mean, minimum and maximum values; (3) snowflake diagrams, in which each of the axes represents the range of one of the key driving forces; (4) analysis of the relationships among the main driving forces of energy-related CO_2 emissions; and (5) sensitivity analysis which examines the relative influence of three of the driving force variables on global energy-related CO_2 emissions.

4. Scenario Database

There have been many analyses of scenarios, including some conducted with the use of databases. For example, the EMF (Weyant, 1993), the IEW (Manne and Schrattenholzer, 1996 and 1997) and the Energy Technology Systems Analysis Programme (ETSAP, see Kram, 1993) have compiled extensive databases of scenarios. The 1994 IPCC evaluation of emissions scenarios used a less formal database (Alcamo *et al.*, 1995, 1996). The scenario database developed for SRES, briefly described in this section, builds on these notable earlier efforts to compile and classify emissions scenarios. The database includes all scenarios collected for the purpose of these earlier efforts as well as more recent scenarios from the literature.

The scenario database was designed to fulfill several objectives. The first objective was to facilitate a thorough review and analysis of the literature. The second objective was to allow for a statistical analysis of all scenarios in the database - to generate distribution functions of the main scenario driving forces, calculate mean and median values, etc. By performing such statistical analyses of the scenarios in the database, the IPCC writing team can ensure that the new scenarios to be developed through the SRES process adequately reflects the range of emissions and input assumptions currently found in the open literature. The third objective is to make the database accessible on a web-site so that data queries, browsing and data retrieval would be possible by remote users as well as to facilitate the entry of new scenarios. This necessitated design of a database that could manage the huge amount of data describing the emission scenarios in a flexible way.

To fulfill these objectives and requirements, the database was designed with a relational structure using Microsoft Access '97. This allows handling large data sets with diverse data types. The relational structure of the database makes it possible to query comparable data sets across the key fields (e.g., driving forces and scenario characteristics), allowing for maximum data flexibility in manipulation, extraction and presentation. The structure of the relational database is illustrated in the Appendix.

At the time of finalizing this paper (August 1998), the database included a total of 428 scenarios from 176 sources. Most of these scenarios are newer than 1994. 290 of the 428 scenarios report global emissions. According to our initial classification, the majority of the scenarios could be characterized as being of a non-intervention type; the rest appear to include some kind of policies for reducing GHG and other emissions, ultimately directed at mitigating climate change.

5. Scenario Driving Forces

Numerous factors influence future emissions paths in the scenarios. Clearly, demographic and economic developments play a crucial role in determining emissions. Other factors are many and it is not possible to devise a simple scheme that accounts for all the influencing forces that are included in the scenarios. They range from human resources such as education, institutional frameworks and lifestyles to natural resource endowments, technological change and international trade.

For the purpose of this paper we choose a simple scheme captured by the so-called Kaya identity. This hypothetical identity represents the main emissions driving forces as multiplicative factors. It establishes a relationship between population growth, per capita value added (i.e., per capita global world product, GWP), energy consumption per unit value added, and emissions per unit energy on one side of the identity, and total CO_2 emissions on the other side (Yamaji *et al.*, 1991)[3].

The advantage of analysis employing the Kaya identity is that it is simple and facilitates at least some standardization in the comparison and analysis of many diverse emissions scenarios. An important caveat is that these driving forces are not independent of each other. In fact, in many scenarios they explicitly depend on each other. For example, scenario builders often assume that high rates of economic growth lead to high capital turnover. This favors more advanced and more efficient technologies resulting in lower energy intensities. Often a weak inverse relationship is assumed between population and economic growth. Thus, the reader should note that the scenario ranges for these main driving forces are not necessarily independent of each other.

In the following we present the scenario ranges for each of the factors in the Kaya identity representing the main (energy-related) emissions driving forces: population, GWP, energy consumption (total consumption and energy intensity)

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[3] $CO_2=(CO_2/E)\times(E/GWP)\times(GWP/P)\times P$, where E represents energy consumption, GWP the gross world product (or global value added) and P population. Changes in CO_2 emissions can be described by changes in these four factors or driving forces.

and carbon intensity. We begin with scenario ranges for CO_2 emissions, represented as a "dependent variable" in the Kaya identity. Then we analyze the other factors, represented as "independent variables" (main emissions scenario driving forces) in the identity. We chose this sequence to present the main scenario driving forces because it corresponds to the way they are represented in the Kaya identity without implying *a priori* any causal relationships among the driving forces themselves and between the driving forces and CO_2 emissions.

6. CO_2 Emissions Ranges

The span of CO_2 emissions across all scenarios in the database is indeed large, ranging in 2100 from ten times the current emissions all the way to negative emissions (due to enhanced carbon sinks, which are included in some scenarios—see footnote 1). There are many possible interpretations of this large range and many good reasons why it should be so large. Common to most of them is the high uncertainty about how the main driving forces might unfold during the next century, such as the population growth, economic development and energy production, conversion and end use.

Figure 1 shows the global CO_2 emission paths from the database as "spaghetti" curves for the period to 2100 against the background of the historical emissions from 1900 to 1990. These curves are plotted against an index on the vertical axis rather than as absolute values due to often large differences and discrepancies for the values assumed for the base year 1990. This is sometimes due to genuine differences among the scenarios (e.g., different data sources, definitions, etc.) and sometimes to different base years assumed in the analysis or simple errors in the calibration[4].

Historically, emissions have increased at an average rate of about 1.7 percent per year since 1900; if that historical trend continues global emissions would double during the next three to four decades. Many scenarios in the database in fact describe such development. However, even by 2030 the range is very large around this value of possible doubling of global emissions. The highest scenarios have emissions four times the 1990 level by 2030 while the lowest are barely above half the current emissions. This divergence continues so that the highest scenarios envisage a ten-fold increase of global emissions by 2100. These high emissions levels would no doubt lead to an alarming increase in atmospheric CO_2 concentrations and could cause significant global climate change. The median scenarios lead to about a three-fold emissions increase over the same time period. This is somewhat lower than the medians observed in the

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[4] The 1990 emissions from energy production and use are estimated by Marland *et al.* (1993) at 5.9 GtC excluding cement production. The 1990 base year values in the scenarios reviewed range from 4.8 (CETA/EMF14, Scenario MAGICC CO2) to 6.4 GtC (ICAM2/EMF14), see Dowlatabadi, *et al.*: 1995, Peck and Teisberg, 1995.

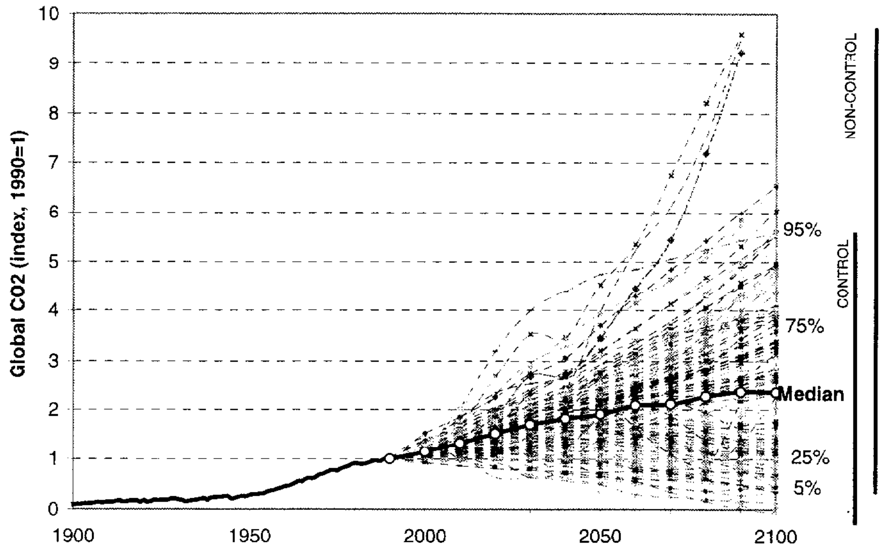

Figure 1. Global carbon emissions: Historical development and scenarios. Emissions are indexed to 1990, when actual global energy-related CO_2 emissions were about 6 GtC. 232 scenarios are included in the figure. Two vertical bars on the right-hand side indicate the ranges for scenarios with emissions control measures (labeled "control") and for those without controls ("non-control"). Data sources: Nakićenović *et al.* (1998) and Morita and Lee (1998).

earlier scenarios comparisons (see Alcamo *et al.*, 1995). Nevertheless, the median emissions path would more than double atmospheric concentrations of CO_2 to approximately 750 ppmv by 2100. (The current value is about 360 ppmv.) A number of scenarios in the low range are consistent with stabilizing concentrations at a relatively benign 450 ppmv.

The spaghetti curves in Figure 1 do not include all of the global emissions paths in the database, but are rather based on a representative sample of scenarios so that they are discernable as individual trajectories in Figure 1. (A plot of all global scenarios would produce a blurred image.) It should be noted that not all emissions paths plotted in Figure 1 increase monotonically; some oscillate from high rates of increase to periods of declining emissions; other paths cross each other. What is important is that on average there is a strong trend towards continuous increases in emissions with most of the scenarios clustering between a small decrease in global emissions over the next century to more than a four-fold increase.

6.1 CO_2 EMISSIONS HISTOGRAMS

The first two histograms (Figures 2A and 2B), give the global carbon dioxide emissions ranges for 2050 and 2100. The first axis shows indexed emissions

(1990=1); the second horizontal axis indicates absolute values by multiplying the index by the 1990 value (6 GtC). The total range is between 3 and 40 GtC, from about half to seven times the current emissions. Half the current emissions level is an important benchmark because the eventual reduction to approximately this level could lead to stabilization of the atmospheric carbon dioxide concentration. Most of the scenarios that have low future emissions include some policy intervention directed at reducing greenhouse gas emissions.

The distribution of emissions in 2050 is asymmetrical, with most of the scenarios clustering in the range between 6 to 18 GtC. The thin tail that extends above this emissions level includes just 15 out of a total of 200 scenarios. Altogether, the distribution implies a substantial increase in global carbon dioxide emissions during the next 60 years.

The distribution of emissions in 2100 is even more asymmetrical than in 2050. The observations portray a structure resembling a tri-modal distribution: those showing emissions of less than 12 GtC (77 scenarios), those with emissions between 12 and 30 GtC (85 scenarios), and those showing emissions of more than 30 GtC (11 scenarios). This is quite similar to the structure of primary energy consumption distribution for 2100 and is not so by chance. The first cluster includes the intervention scenarios; the second and third clusters most of the non-intervention cases. It is very likely that the majority of the scenarios foresee a substantial contribution of fossil energy sources to total energy consumption in the year 2100; thus in the first approximation, carbon dioxide emissions can be expected to be proportional to energy consumption. The median is 15 GtC, surrounded by the centers of the first two modes, the first about 9 and the second about 18 GtC.

The highest non-IS92 scenarios in 2100 are MIT/EMF 14 (Standardized reference scenario), RICE (reference case), and RICE/EMF 14 (Modeler's Choice). The lowest CO_2 emissions are found in the following models: IMAGE 2.1 (Stabilization at 350 ppmv and Stabilization at 450 ppmv); IMAGE/EMF14 (Ecosystem); IIASA/EMF14 (Agriculture); CETA/EMF14 (Limited temperature change, Accelerated technology development); IIASA–WEC (C cases); MERGE/EMF14 (Limited temperature change).[5]

Published energy-related emissions vary by a factor of 14 between the highest and lowest scenarios for 2050, and by a factor of 52 between the highest and lowest scenarios for 2100. In all, 173 scenarios were used to generate this histogram. (Not all 290 scenarios that report global CO_2 emissions cover the whole period to the year 2100.)

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[5] The scenarios were taken from the following literature sources: Alcamo and Kreileman 1996, Peck and Teisberg 1995, IIASA-WEC 1995, and Manne and Richels 1996, respectively.

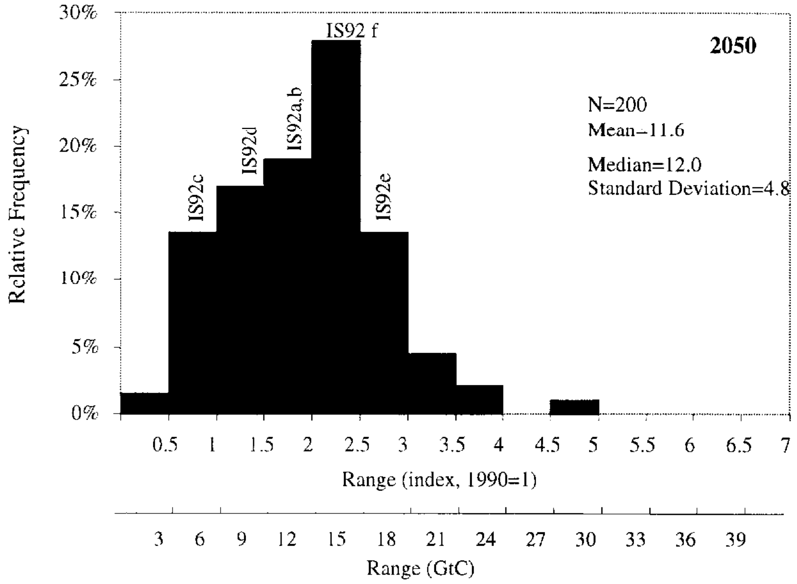

Figure 2A. Histogram of global CO_2 emissions in 2050 for different scenarios. For reference, values of the IS92 scenarios are indicated.

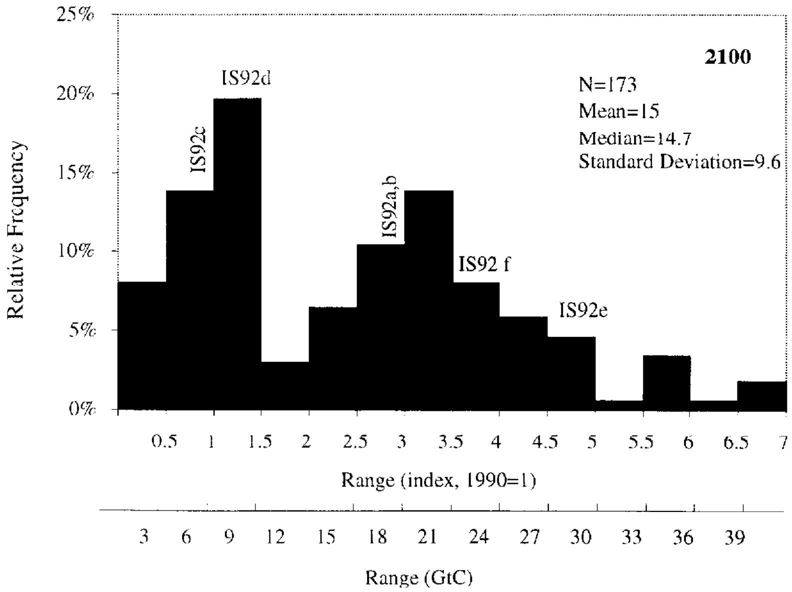

Figure 2B. Histogram of global CO_2 emissions in 2100 for different scenarios in the database. IS92 scenario values are indicated for reference.

7. Population Projection Ranges

Population is one of the fundamental driving forces of future emissions. Yet most of the population projections for the emissions scenarios are taken from the literature and are exogenous inputs in most models used to formulate emissions scenarios. Today there are three main research groups that project global population – United Nations (UN, 1998), World Bank (Bos and Vu, 1994) and IIASA (Lutz *et al.*, 1997). (For more details see the article by Stuart Gaffin in this special issue.) For the purpose of this comparison of emissions scenarios, most of the central population projections lead to a doubling of global population by 2100 to more than ten billion people compared to 5.3 billion in 1990. In recent years the central population projections for the year 2100 have declined somewhat but are still in line with a doubling by 2100. For example, the latest United Nations (1998) medium-low and medium-high projections indicate a range of between 7.2 and 14.6 billion people by 2100, with the medium scenario at 10.4 billion. The IIASA central estimate for 2100 is also 10.4 billion with 95 percent probability that world population would exceed six and be lower than 17 billion (Lutz *et al.*, 1997).

While all scenarios require some kind of population assumptions, relatively few of them are reported in the database. Figure 3 illustrates global population projections in the database. Of the 428 scenarios currently documented in the database, only 59 report their underlying population projections. For this small sample, the range is from more than six to about 19 billion in 2100 with the central or median estimates in the range of about ten billion. Thus, the population assumptions in the emissions scenarios appear to be broadly consistent with the recent population projections with the caveat that only a few underlying projections have been reported in the database.

Figure 3 contrasts the alternative population projections with the historical developments. The long-term historical population growth rate has been on average about one percent per year during the last two centuries and at about 1.3 percent per year since 1900. Currently, the world's population is increasing at about two percent per year. The scenarios and other global population projections envision a slowing population growth in the future. The most recent doubling of the world population took approximately 40 years. Even the highest population projections in Figure 3 require 70 years or more for the next doubling while roughly half of the scenarios do not double population during the 21st century. The lowest average population growth across all projections is 0.1 percent per year, the highest is 1.2 percent per year, and median is about 0.7 percent per year.

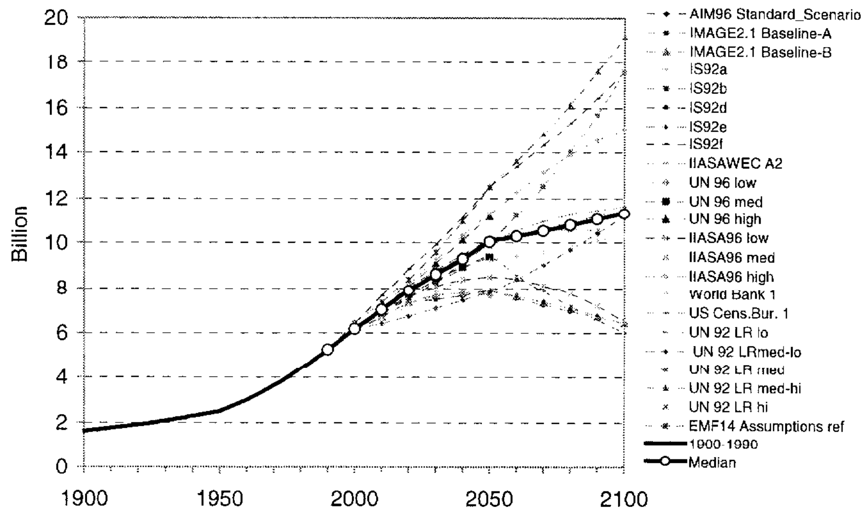

Figure 3. Global population: Historical development and scenarios. Data source: Durand (1967), Demeny (1990), UN (1996) and Morita and Lee (1998).

Even though the range of global population projections in Figure 3 accurately reflects the recent literature, it is interesting to note that the population projections used for these emission scenarios are not evenly distributed across the whole range. Instead, they are grouped into three clusters. The middle cluster is representative of the central projections with the range of about 9 to fewer than 12 billion people by 2100. The other two clusters mark the highest and the lowest population projections available in the literature with about six billion on the low end and between 14 and 19 billion at the high end.

Despite these large ranges among alternative global population projections, the variation in this factor compared to the base year is the smallest of all scenario driving forces considered in this comparison. Compared with 1990 values, the factor increase varies from less than one to less than four.

8. Gross World Product (GWP)

Economic development and growth are fundamental prerequisites for achieving an increase in living standards. It is thus not surprising that the assumptions about the economic development constitute among the most important determinants of emissions levels in the scenarios. At the same time, the economic growth prospects are among the most uncertain determinants of future emissions. This is reflected in the very wide range of economic development paths assumed in the scenarios. Figure 4 shows the future increase in GWP

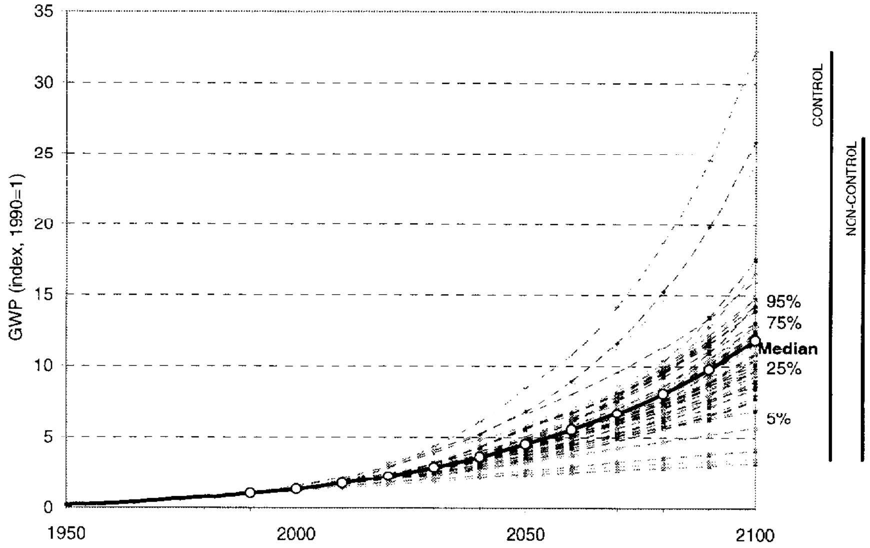

Figure 4. Global Economic output: Historical development and 167 scenarios. Data source: UN (1950–1995), Morita and Lee (1998).

compared with the historical experience since 1950. Due to the relatively large differences in the base year data, the GWP paths are plotted as an index and spliced to historical data in 1990.

The historical GWP growth rate has been about 4 percent per year since 1950; in the scenarios the average growth rates to 2100 range from 1.1 percent per year to 3.2 percent per year, with the median value of 2.3 percent per year. This translates into a GWP level in 2100 that varies from 3.5 (IS92c) to more than 32 (FUND/EMF, Modeler's choice) times the 1990 GWP. The 1990 GWP was about US$20 trillion, which translates into the range of about US$70 to more than US$640 trillion by 2100.

At the same time, Figure 4 indicates that this full range includes a few noticeable outliers toward the high and low of future GWP development. The rest of the scenarios are grouped much more closely together compressing the range to a factor increase of about 7 to 17 times compared to 1990. The degree of clustering is discussed in greater detail in the histograms that follow.

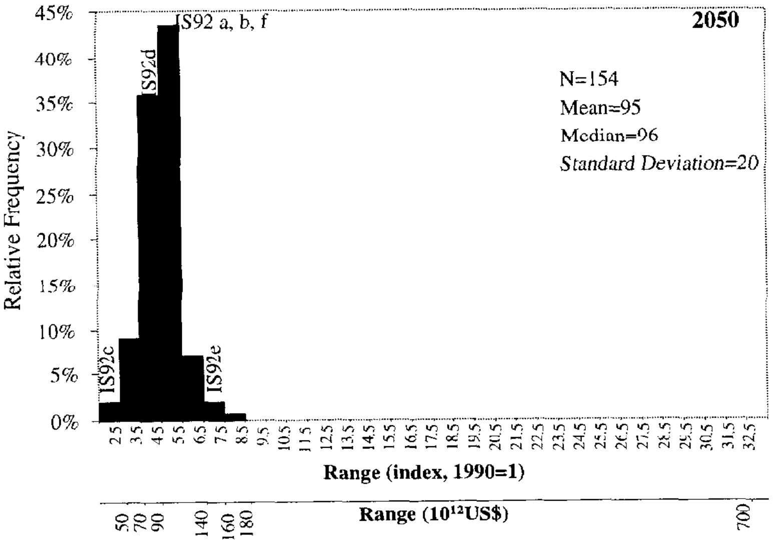

Figure 5A. Histogram of GWP in 2050 for different scenarios in the database. For comparison, values for the IS92 scenarios are indicated.

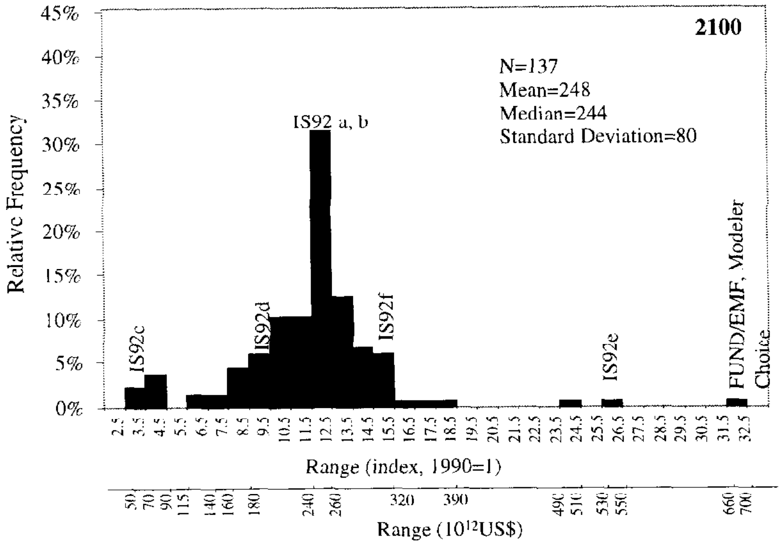

Figure 5B. Histogram of GWP in 2100 for different scenarios in the database.

8.1 GROSS WORLD PRODUCT HISTOGRAMS

Figures 5A and 5B depict the range of GWP in 2050 and 2100 across all scenarios in the database[6]. The first horizontal axis shows the factor increase of GWP compared with the 1990 value (about US$20 trillion). The second horizontal axis multiplies the index by the 1990 GWP to indicate absolute values for each histogram.

For 2050 most of the scenarios cluster in a rather narrow range around the value of about US$100 trillion. In total, 154 scenarios were used to derive the histogram for 2050.

This picture changes radically for the year 2100, with a very wide variation of GWP values, from about US$50 to US$700 trillion and a median of US$240 trillion. As expected, the distribution of emissions becomes significantly wider as the scenarios extend further into the future. Most of the distribution is concentrated between about US$160 and US$320 trillion, with very thin and asymmetric tails. There is a very strong peak of values around US$250 trillion, which apparently represents a kind of conventional wisdom, based on an average economic growth rate of about 2.3 percent per year. The frequency of the mode is smaller in 2100 than in 2050, indicating that the scenarios agree less about the central estimated GWP. There are no distinguishable clusters of GWP for non-intervention and intervention scenarios; interestingly, both the maximum and minimum are observed for intervention cases (FUND/EMF14, Modeler's Choice (Tol, 1995) and YOHE/EMF14, Ems/MOD (Yohe, 1995)). For 2050 and 2100 the GWP for the IS92a and b scenarios are the same as the median for all scenarios reviewed. 137 different scenarios were used to derive this histogram (Pepper *et al.*, 1992).

8.2 POPULATION AND GWP RELATIONSHIPS

The scenarios in the database portray a weak relationship between population and economic growth: the correlation is slightly negative. Scenarios that lead to very high GWP are generally associated with central to low population projections, while high population projections do not lead to the highest GWP scenarios.

Figure 6 illustrates some of the relationships between population and GWP in the scenarios. It compares only 39 scenarios because the information about population assumptions is available for only a few scenarios. In most of them, global population transition is achieved during the next century and stabilization occurs at population between ten to 12 billion people. Generally, this is associated with relatively high levels of economic development in the range from US$200 to US$500 trillion. Scenarios on the lower end of this scale are

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[6] Because model base years and base year values differ, values are indexed to 1990 values.

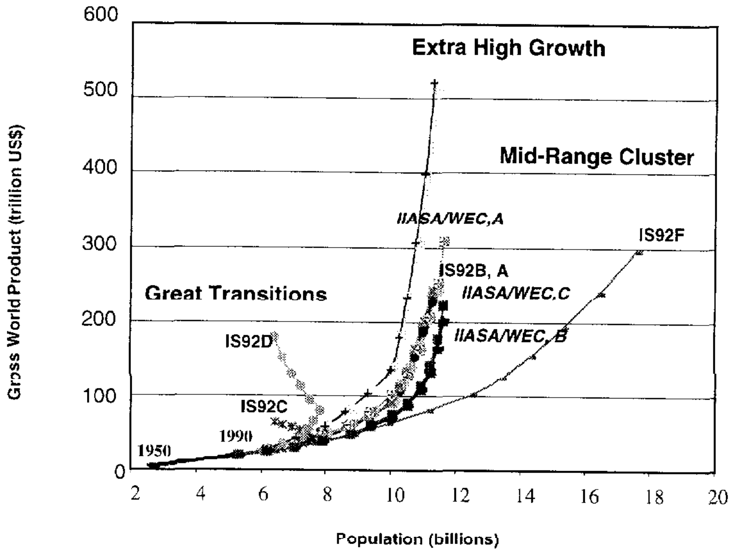

Figure 6. GWP and population growth: Historical development and scenarios in the database

labeled collectively as the "mid-range cluster" (including all IIASA–WEC scenarios (IIASA-WEC, 1995 and Nakićenović *et al.*, 1998), IS92a and b (Pepper *et al.* 1992), and AIM96 (Matsuoka *et al.*, 1994) while the two highest scenarios are labeled as the "extra high growth" (IS92e (Pepper *et al.*, 1992)) and IMAGE 2.1, Baseline-C (Alcamo and Kreileman, 1996)) cases.

One scenario, IS92f, shows high population growth (over 18 billion people by 2100) with comparatively low economic growth (about the same level as the mid-range cluster of scenarios, approximately US$300 trillion). On the other side of the scale are the two IS92 variants (c and d (Pepper *et al.*, 1992)) with low population projections (about six billion people by 2100). They are labeled as the "great transitions" scenarios because they lead to relatively high economic growth paths with low global populations.[7]

9. Primary Energy Consumption Ranges

Primary energy consumption is another of the fundamental determinants of GHG emissions. Clearly, high energy consumption tends to cause high emissions. However, what is more important for emissions is the structure of energy systems. High carbon intensities of energy—namely high shares of fossil energy sources, especially coal, in total energy consumption—lead to scenarios

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[7] For a description of possible scenario structures and classifications, see Gallopin *et al.* (1997).

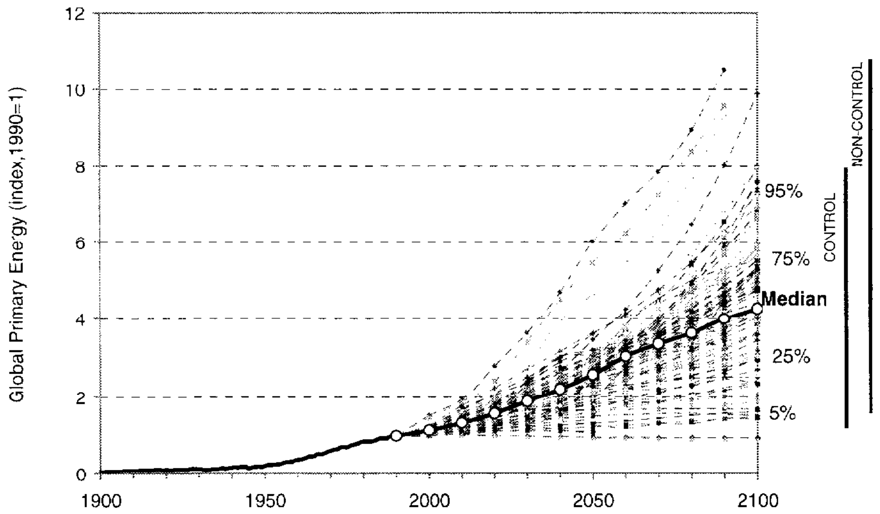

Figure 7. Global primary energy consumption: Historical development and scenarios. Data sources: Nakićenović *et al.* (1998) and Morita and Lee (1998)

with highest carbon emissions. We will first compare the primary energy paths of different scenarios and in the next section consider the issue of energy carbon intensity.

Figure 7 shows the primary energy consumption paths in the scenarios and the historical development since 1900. Due to the relatively large differences in the base year values the primary energy consumption paths are plotted as an index and spliced to the historical data in 1990. In 1990 primary energy was about 9 Gtoe.

On average the global primary energy consumption has increased at more than two percent per year (fossil energy alone has risen at almost three percent per year) since 1900. In the scenarios the average growth rates to 2100 range from –0.1 percent per year to 2.4 percent per year, with the median value of 1.3 percent per year.

Figure 7 indicates that this full range includes a few noticeable outliers, especially non-control scenarios toward the high of energy consumption levels. The rest of the scenarios are grouped more closely together compressing the range to a factor increase of about one to eight times compared to 1990. The degree of clustering is discussed in greater detail in the histograms that follow.

9.1 PRIMARY ENERGY CONSUMPTION HISTOGRAMS

The last two histograms, Figures 8A and 8B, give the global primary energy consumption ranges for 2050 and 2100, indexed to 1990. The second horizontal axis indicates absolute values. The total range in 2100 is between 9 and 90 Gtoe,

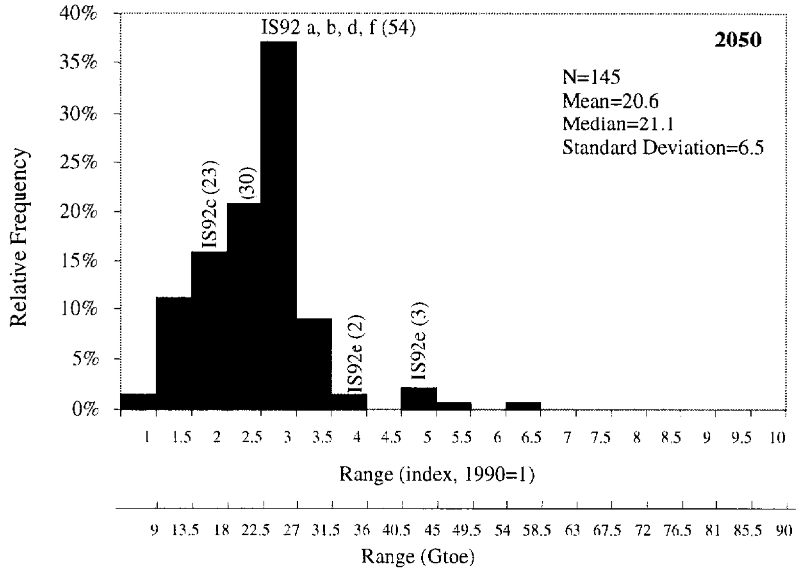

Figure 8A. Histogram of global primary energy in 2050 for different scenarios in the database. IS92 scenario values are indicated for reference.

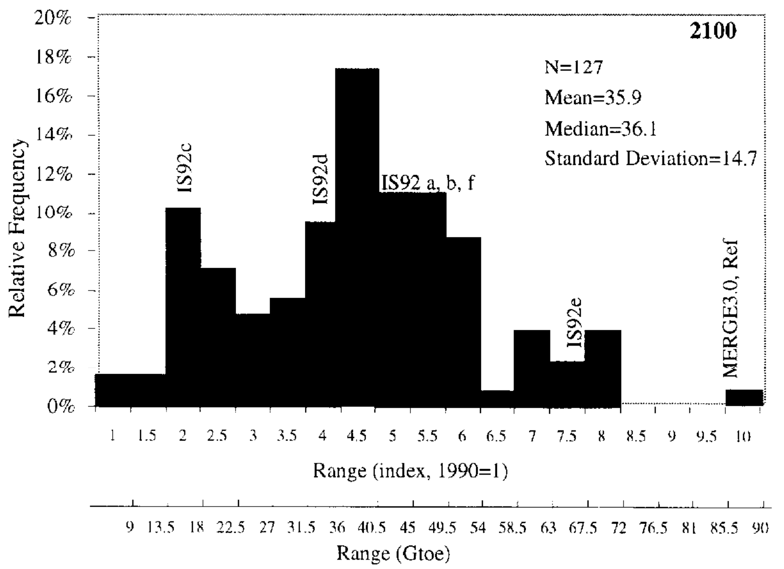

Figure 8B. Histogram of global primary energy in 2100 for different scenarios in the database. IS92 scenario values are indicated for reference.

or a factor ten difference. This factor range is nearly identical to the factor range for GWP (10.7) and much larger than the factor range for population.

The distribution of primary energy consumption in 2050 is asymmetrical, with a long but thin tail toward high levels. Most of the distribution is between 14 to 32 Gtoe, or about 1.5 to 3.5 times the 1990 level of consumption. The higher value corresponds with the continuation of historical rates of global primary energy consumption growth of about 2.2 percent per year during the 60 year period. Most of the scenarios cluster around 23 Gtoe, which is about a factor three growth compared to 1990. A total of 145 different scenarios were used to derive this histogram.

In 2100 the distribution of primary energy consumption is much less concentrated and covers the full range, from no increase above the 1990 level to a factor 10 increase (to 90 Gtoe). However, there are only a few observations toward these extreme values of the two distribution tails. For example, MERGE 3.0 (non-intervention scenario) is a high-end outlier in 2100, with a projection of approximately 85.5 Gtoe. The rest of the observations portray a very interesting structure resembling a tri-modal distribution. The first mode is around 18 Gtoe and reflects mainly intervention scenarios. The second, around 40 Gtoe, includes some intervention scenarios (mostly scenarios that stabilize CO_2 concentrations at 550 ppm) as well as non-intervention scenarios. The last mode (about 67 Gtoe) includes only non-intervention scenarios. The median of the whole distribution is at 36 Gtoe. It is also interesting to note that the continuation of the historical growth rate of about 2.2 percent per year corresponds to a factor 11 growth (about 100 Gtoe in 2100), well above any values observed in the database. Thus, in contrast to data for 2050, all scenarios in 2100 foresee a level of primary energy consumption that is lower than trend extrapolation would lead one to expect. Altogether, 127 different scenarios were used to derive this histogram.

9.2 RELATIONSHIPS BETWEEN PRIMARY ENERGY AND GWP

Most of the scenarios in the database portray a clear relationship between primary energy and GWP. In all scenarios, economic growth outpaces the increase in energy consumption, leading to substantial reductions in the ratio of primary energy consumption to GWP (energy intensity). Individual technologies progress, inefficient technologies are retired in favor of more efficient ones, the structure of the energy system and patterns of energy services changes; these factors reduce the amount of primary energy needed per unit of GWP. With all other factors being equal, the faster the economic growth, the higher the turnover of capital and the greater the decline in energy intensity.

These long-term relationships between energy and economic development are reflected in the majority of scenarios and are consistent with historical

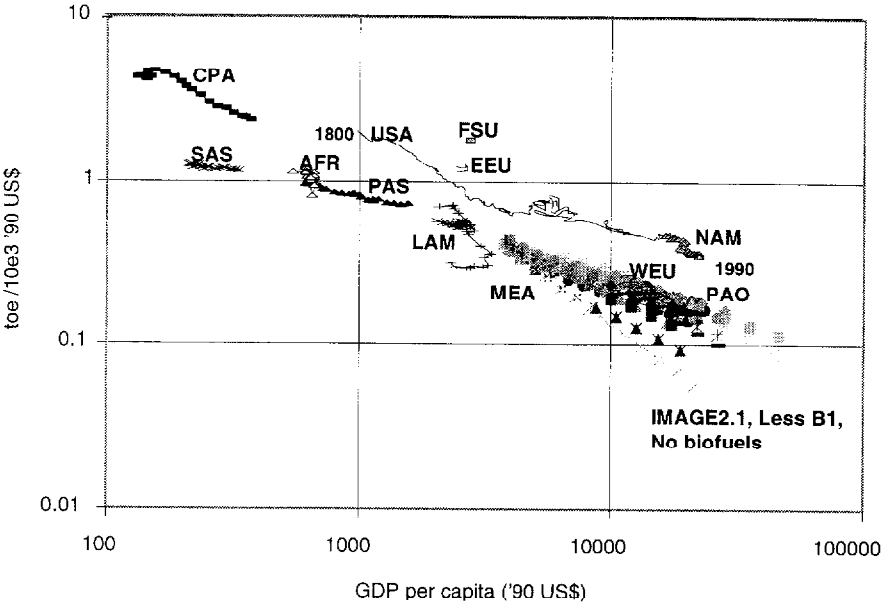

Figure 9. Primary energy intensity versus GDP per capita: Regional historical developments and global scenarios. Data sources IEA (1993), World Development Report (1993), Nakićenović *et al.* (1998) and Morita and Lee (1998)

experience across a range of alternative development paths observed in different countries (as represented in the database).

Figure 9 shows the historical relationship since 1970 between energy intensity and gross domestic product (GDP) per capita for the world regions; North America (NAM), Latin America and Caribbean (LAM), Western Europe (WEU), Eastern Europe (EEU), Former Soviet Union (FSU), Middle East and North Africa (MEA), Sub-Saharan Africa (AFR), Centrally Planned Asia and China (CPA), South Asia (SAS), Other Pacific Asia (PAS) and Pacific OECD (PAO). This shorter record of development is contrasted with the experience of the USA since 1800. In all cases, economic growth is associated with a reduction in energy intensity; the level of energy intensities in developing countries today is generally comparable with that of the now industrialized countries when they had the same level of per capita GDP. The historical experiences illustrate that different countries and regions can follow different development paths; moreover, there are some persistent differences in energy intensities even at similar levels of per capita GDP.

Global energy intensities diverge across different scenarios within a "cone" on Figure 9 that starts in the base year 1990. This result clearly illustrates that there is a persistent inverse relationship between economic development and

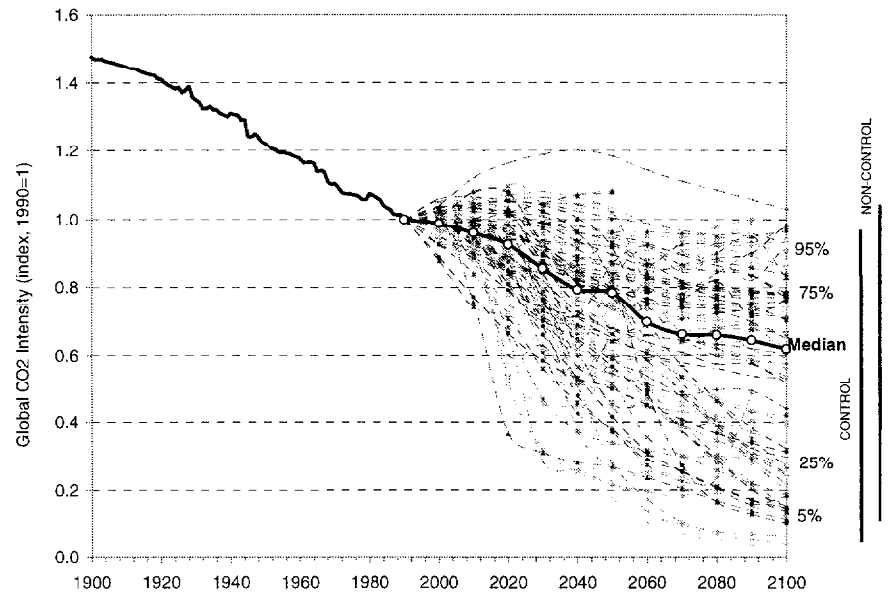

Figure 10. Global Decarbonization of primary energy: Historical development and scenarios. Data source: Nakićenović (1996), Morita and Lee (1998).

energy intensity across the wide range of scenarios in the database despite numerous differences among them.

10. Carbon Intensity and Decarbonization

Decarbonization denotes the declining average carbon intensity of primary energy over time (see Kanoh, 1992). Although the decarbonization of the world's energy system shown in Figure 10 is comparatively slow (0.3 percent per year), the trend has persisted throughout the last two centuries (Nakićenović, 1996). The overall tendency toward lower carbon intensities is due to the continuous replacement of fuels with high carbon content by those with low carbon content; however, intensities are currently increasing in some developing regions.

The carbon intensities of the scenarios are shown in Figure 10 as an index that was spliced in the base year 1990 to the historical development. The median of all the scenarios indicates the continuation of the historical trend with a decarbonization rate of about 0.4 percent per year.

The scenarios that are most intensive in use of fossil fuels lead to practically no reduction in carbon intensity. The highest rates of decarbonization (up to 3.3 percent per year) are from scenarios that envision a complete transition in the energy system away from carbon-intensive fossil fuels.

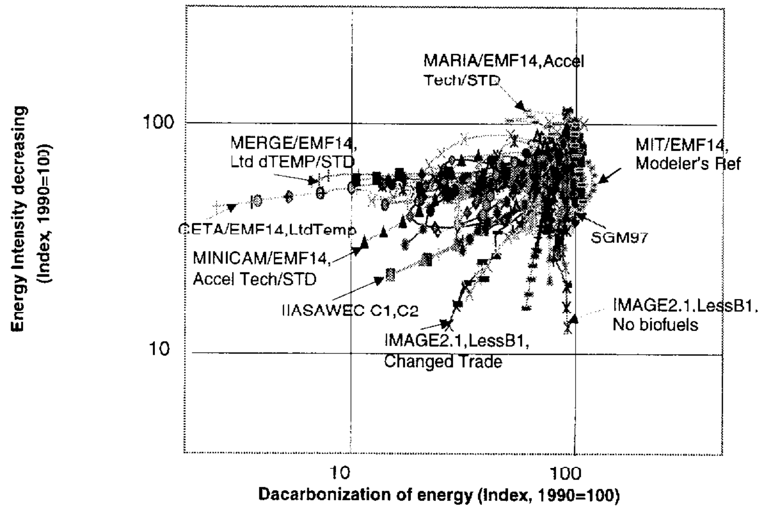

Figure 11. Global Decarbonization and deintensification of energy (1990–2100). Data source: Morita and Lee (1998).

Figure 11 illustrates the relationships between energy intensities of GWP and carbon intensities of energy across the scenarios in the database. Both intensities are shown on logarithmic scales. The starting point is the base year 1990 normalized to an index (1990=100) for both intensities. Scenarios that unfold horizontally are pure decarbonization cases with little structural change in the economy; scenarios that unfold vertically indicate reduction of energy intensity of economic activities with little change in the energy system. Most scenarios stay away from these extremes and develop a fan-shaped pattern—marked by both decarbonization and declining energy intensity—across the graph in Figure 11.

The fan-shaped graph illustrates the notable differences in the policies and structures of the global energy systems among the scenarios. For example, MERGE/EMF (Stblz ppm, STD), IIASA-WEC (C1,C2) , CETA/EMF (Accel Tech/Mod), CETA/EMF (Ltd, dTemp/STD) , MINICAM/EMF14 (Accelerated Technology), IMAGE2.1 (Less B1 Changed Trade)[8] scenarios have to achieve the largest degree of decarbonization over 2100. In IMAGE2.1 (Less B1, Changed Trade), IIASA-WEC (C1, C2), CETA/EMF (Ltd, dTemp/STD) and MINICAM/EMF14 (Accelerated Technology) scenarios this decarbonization is achieved largely through energy efficiency improvements, while in CETA/EMF (Accel Tech/Mod) and MERGE/EMF(Stblz ppm, STD) decarbonization is

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[8] The "LESS B1" scenario assumptions are used for all scenario factors except for the trade of modern biomass (Alcamo and Kreileman, 1996). This scenario makes the assumptions that a large amount of modern biomass is produced in Canada, Latin America and CIS and exported to Africa and Asia. Sulfur emissions are kept constant at their 1990 level.

mainly the result of lower carbon intensity due to vigorous substitution of fuels.[9,10]

The extreme cases are SGM scenarios for 1990–2050 where significant energy intensity improvements are not accompanied by decarbonization, and MERGE/EMF (Stblz ppm, STD) scenario where decarbonization in 1990–2050 is not accompanied by significant improvements in energy intensity.

A few scenarios, such as MARIA/EMF14-Stnd REF[11]; MARIA/EMF14-Accel Tech/STD[12] and MARIA/EMF-Opt Ems/STD[13] follow a path that is opposite from other scenarios: decarbonization of primary energy with decreasing energy efficiency until 2040. After 2040 the ratio CO_2 per unit of primary energy increases—in other words, recarbonization.

11. Other Scenario Comparisons

11.1 SNOWFLAKE DIAGRAMS

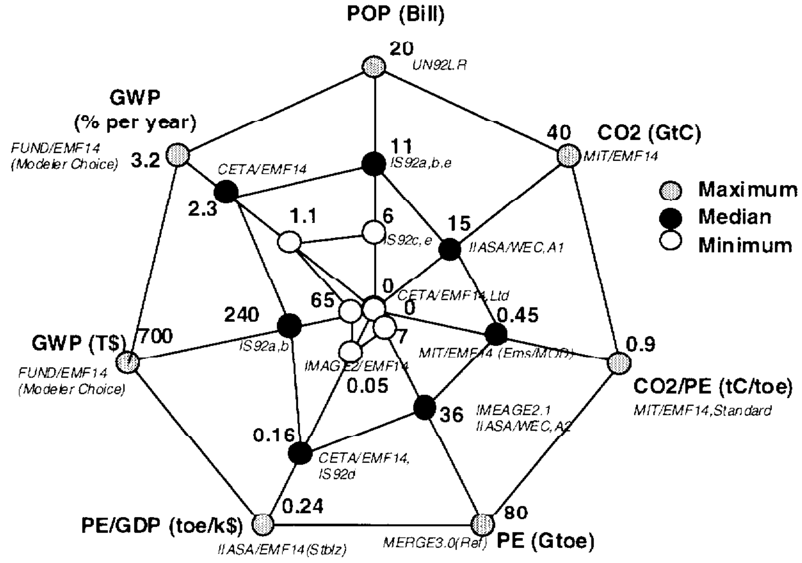

Figure 12. Global Scenarios: Minimum, maximum and median values in 2100.

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[9] The scenarios were taken from the following literature sources: Alcamo and Kreileman, 1996, Manne and Richels, 1995, IIASA-WEC, 1995, Peck and Teisberg, 1995, Manne and Richels, 1996.

[10] Thus, for example, the total fossil fuels consumption in CETA/EMF (Accel Tech/Mod) scenario decreased from 28 percent in 1990 to 4 percent in 2100 (Peck and Teisberg, 1995).

[11] Standardized Reference Case

[12] Accelerated Technology / STD Input

[13] Optimal Carbon Emissions / STD Input

Figure 12 illustrates these distributions in the form of a snowflake. It shows carbon dioxide emissions as well as 6 indicators related to the four main driving forces: population, GWP (absolute level and growth rate), primary energy consumption (absolute level and energy intensity), and carbon intensity of energy.

The first tick mark (open circle) denotes the minimum value of the scenario distribution, the middle tick mark (solid circle) the median value, and the last tick mark (shaded circle) the maximum value. Also shown are the values for some typical scenarios from the database.

The minimum, median and maximum values are connected into snowflakes. However, this can be very misleading: the values of one axis are linked to values on another in some cases because of established causal relationships between the variables and in other cases because of the inherent structure of the models used to formulate the scenarios.

Therefore, merely connecting the median values into a snowflake does not necessarily yield a consistent or logically possible scenario. Actual scenarios may fall into the median range on some axes and on more extreme values on another. It is thus useful to use snowflakes for purposes of scenario classification and interpretation only and not for scenario design, since the latter could lead to logical inconsistencies.

11.2 SENSITIVITY ANALYSIS

A sensitivity analysis reveals the relative influence of three driving force variables in the Kaya identity (GWP, energy intensity, and carbon intensity) on energy-related CO_2 emissions as the "dependent" variable in the identity. This representation does not imply a causal relationship among the driving forces and CO_2 emissions (see Figure 13 and Table 1). It is merely a sensitivity analysis of the variation across the scenarios in the database. Population was not included in the analysis because information about population assumptions is not available for all the scenarios reviewed. Sensitivity is expressed in GtC as the change in global emission relative to IS92a, resulting from changes in GDP, energy intensity and carbon intensity derived from the extreme minimum/maximum of the all scenarios.[14] Extreme values for each of the three driving force variables are compared with the IS92a scenario at three time points: 2020, 2050 and 2100. Also shown is the range for policy-intervention scenarios. This is based on a preliminary classification of scenarios and can be expected to change as more

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[14] For instance, the emission impact of a difference in economic activity (GWP) between IS92a and the min/max values of all scenarios up to year i were calculated as:

$\Delta\, GWP_i = C_i IS92a\ (GWP_i\ index(min/max) * GWP1990\ IS92a * (PE/GWP)_i\ IS92a * (C/PE)_i\ IS92a\ )$, where C is CO_2 emissions, GWP is gross world product, PE/GDP is primary energy intensity, C/PE is carbon intensity of primary energy.
For reasons of data consistency, min/max values are calculated using IS92a 1990 base year values and applying respective min/max indexes from the sample of all scenarios.

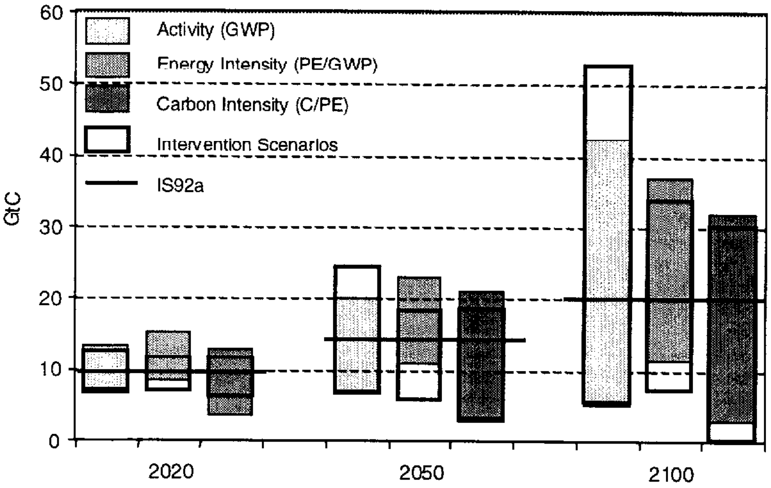

Figure 13. Sensitivity Analysis of global energy-related carbon emissions by main scenario driving forces compared to IS92a scenario.

information about the scenarios is compiled. The IS92a scenario was used as the reference for this sensitivity analysis because the values for many driving forces (GWP, primary energy, population and energy intensity) in this scenario are quite close to the median values derived from the database. Moreover, the IS92a scenario is frequently used as a benchmark scenario.

This sensitivity analysis indicates that the carbon intensity of energy is the most variable of the three driving forces in determining CO_2 emissions over the time horizon up to 2020. Economic growth and energy intensity have lower and approximately equal variability. After this period, the relative variability of these three factors changes. By 2050, all three driving forces have approximately equal influence on the range of projected emissions; thereafter GWP growth becomes clearly the dominant driving force, followed by carbon intensity and then energy intensity.

Improvements in energy efficiency that reduce energy intensity are often highlighted as the most important single measure for reducing CO_2 emissions. It is interesting that the sensitivity analysis confirms the importance of these measures, but it also clearly shows that the structure of the energy system, as reflected in carbon intensity, is more important in the medium term and that the GWP growth rate is the single most important driving force of CO_2 emissions in the scenarios in the longer-term. Both carbon intensity and GWP growth exert higher influence on CO_2 emissions than energy intensity.

Table 1. Comparison of impact of range of driving forces on energy-related CO_2 emissions (difference to IPCC IS92a scenario in GtC).

			Δ GDP	Δ PE/GDP	Δ C/PE
2020		Non-Intervention Cases			
	Minimum		−2.5	−1.5	−6.0
	Maximum		3.3	5.3	2.8
2020		Intervention Cases			
	Minimum		−3.2	−3.1	−3.8
	Maximum		2.6	1.7	1.4
2050		Non-Intervention Cases			
	Minimum		−6.2	−2.5	−9.6
	Maximum		6.6	9.8	7.7
2050		Intervention Cases			
	Minimum		−6.6	−7.5	−10.3
	Maximum		11.2	5.0	5.0
2100		Non-Intervention Cases			
	Minimum		−14.5	−8.6	−16.9
	Maximum		22.6	16.9	11.9
2100		Intervention Cases			
	Minimum		−14.3	−12.4	−19.8
	Maximum		32.9	14.0	10.1

Conclusion

We had two objectives in writing this paper. First was a description of the database, its structure, and the process of assembling the data that it now contains. The database both provides a valuable snapshot of the state-of-the-art in emissions modeling and scenarios and allows initial evaluations of the relative importance of various scenario driving forces. The second objective was to conduct an initial analysis of the state of the art as represented by the database, including specifically a preliminary evaluation of main scenario driving forces.

The factor range for population projections is the smallest (about 3 in 2100), which reflects that there is relatively high consensus among demographers and that relatively few CO_2 emission scenarios include reporting of underlying assumptions for population. The range in 2100 projections for both gross world product and primary energy consumption vary by a factor of 10. Carbon intensity of energy varies by nearly two orders of magnitude in the year 2100. Carbon intensity is a primary indicator of the degree of technological change. Especially for the intervention scenarios, the share and type of fossil fuels—carbon intensity—is the most important driving force in medium-term projections. Over the longer-term, projections for economic development are the most important factor leading to the variation in projected CO_2 emissions.