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Prof. Nebosja Nakicenovic und
Dr. Keywan Riahi:

Model Runs With MESSAGE in the Context of the Further Development of the Kyoto-Protocol

Externe Expertise für das WBGU-Sondergutachten
"Welt im Wandel: Über Kioto hinausdenken.
Klimaschutzstrategien für das 21. Jahrhundert"

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Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen
Geschäftsstelle
Reichpietschufer 60–62, 8. OG.
10785 Berlin

Telefon (030) 263948 0
Fax (030) 263948 50
E-Mail wbgu@wbgu.de
Internet http://www.wbgu.de

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FINAL REPORT

submitted to the
Secretariat of the
German Advisory Council on Global Change

Contract Nr. WBGU II/2003

Principal Investigators
Prof. Nebojsa Nakicenovic and Dr. Keywan Riahi

IIASA Contract No. 03-116

August 25, 2003

International Institute for
Applied Systems Analysis
Schlossplatz 1
A-2361 Laxenburg, Austria

Tel: +43 2236 807 0
Fax: +43 2236 71313
E-mail: info@iiasa.ac.at
Web: www.iiasa.ac.at

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1 Introduction

The objective of this study is to analyze the feasibility and the technologic and economic implications of scenarios that fulfill the stated objectives of the Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC, 1992), namely to lead to a stabilization of atmospheric concentrations of greenhouse gases (GHGs), as exemplified by the main anthropogenic greenhouse gas – CO_2.

The stabilization levels are to be achieved by 2100 in this study and are very ambitious and stringent (400 to 450 ppmv). They embrace a precautionary principle approach at the lower bounds of atmospheric stabilization levels, assumed[1] to be consistent with the UNFCCC language of a "not dangerous anthropogenic interference with the climate system". These "climate stabilization" scenarios are imposed on a number of "background" scenarios of overall demographic, economic, and technologic development drawing on the Special Report on Emissions Scenarios (SRES, Nakicenovic *et al.*, 2000) by the Intergovernmental Panel on Climate Change (IPCC), that assessed the uncertainties on future GHGs in absence of climate policies.

Altogether three SRES background scenarios are further analyzed in this study: SRES-A1, SRES-B1, and SRES-B2. Scenarios A1 and B1 embrace a "sustainable development" paradigm, with the SRES-A1 scenario focusing of the economic and social dimensions (income growth and disparity reduction) and the SRES-B1 scenario focusing in addition also on the environmental dimension (resource conservation and control of traditional pollutants with exception of GHGs) of the "three pillars" (social, economic, environmental) of sustainable development. The more intermediate, "dynamics as usual" scenario SRES-B2 is also analyzed as a means of comparison – even if its assumed stringent climate stabilization target (400 ppmv atmospheric concentration of CO_2) may not necessarily be consistent with the more cautious geopolitical, economic and technologic outlook described in the SRES-B2 background scenario storyline.

Compared to the IPCC SRES report (reporting on so-called climate non-intervention scenarios) and the IPCC Third Assessment Report (TAR) that analyzed various levels of CO_2 stabilization imposed on the SRES background scenarios, the present scenarios differ in a number of aspects.

First of all, only three SRES background scenarios are analyzed in this study, reflecting the interest of the study sponsor (WBGU) as well as time and financial constraints for the analysis. In contrast, IPCC recommended that at least six so-called illustrative SRES scenarios be used in the assessments of climate change as they span much of the uncertainties in emissions and their underlying driving forces.

Second, both the background as well as the stabilization scenarios differ to both the IPCC SRES and TAR scenarios with respect to a number of additional constraints imposed on deployment of zero-carbon options (nuclear, biomass, hydropower, and carbon sequestration), again reflecting the interest of the study sponsor (and henceforth referred to as "WBGU constraints").

Third, the scenarios differ (slightly) from those presented in the IPCC SRES and TAR in terms of continued model improvement such as a different calibration of the year

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[1] This assumption is to a degree arbitrary as conclusive scientific evidence is lacking of what could constitute a level of "dangerous interference with the climate system" due to persistent uncertainties on climate sensitivity and on the impacts (market and non-market) of any given level of realized global warming.

2000 values for which (contrary to SRES and TAR) actual energy and GHG emissions statistics are now available as well a full reflection of the current outlook on the implementation of the UNFCCC Kyoto Protocol in case of the climate stabilization scenarios.

Finally, the scenarios reported in this study are characterized by a number of specific methodological features:

First, and most importantly, all of them embrace a social planner, inter-temporal optimization framework, reflecting current state-of-art in climate policy modeling consistent with IPCC SRES and TAR methodology.

Second, in case of climate stabilization, the scenarios assume (again consistent with prevailing economic theory) a strict separation of the economic issues of equity and efficiency. Thus, the issue of allocation emission rights is separated from the issue of economic efficiency in achieving prescribed emissions reduction profiles, leading to atmospheric CO_2 stabilization. In other words, the scenarios assume international agreement on ultimate climate stabilization goals (and hence on cumulative carbon emissions) as well as on the allocation of resulting GHG emission entitlements (where two variants of a model suggested by the study sponsor WBGU labeled “contraction and convergence” of per capita emission entitlements are analyzed here), whereas the amount of actual emission reduction is assumed to operate under the criterion of economic efficiency (global cost minimization, or rather international marginal abatement cost equalization), assuming the existence of a perfect global market of tradable emission permits.

Third, a distinguishing (and pioneering) feature of the scenario methodology developed at IIASA is the coupling of both “top-down” (macroeconomic) and “bottom-up” (engineering) perspectives of global optimization models addressing climate change mitigation policies. Thus, the scenarios presented in this study, no longer suffer from the customary dichotomy and discrepancy in the interpretation of climate policies between macro-economic and engineering modeling approaches.

These methodological issues need to be borne in mind when interpreting the study results in-as-far as the triple postulates of a global social planner, cost minimization under existence of an agreement on emission entitlements as well as of perfectly functioning markets in emission permits trade result in a rather optimistic outlook on feasibility (and costs) of climate stabilization scenarios, compounded by the fact that the “sustainable development” base case scenarios (with exception of the SRES B2 scenario) on which these climate stabilization scenarios are imposed already portray an optimistic baseline projection of availability and costs of environmentally benign technology, easing subsequently the achievement of ambitious climate stabilization targets.

The plan for the remainder of the study report is as follows. After the introductory Chapter 1, the methodology underlying the present scenario study is described in more detail in Chapter 2, presenting both an overview of the IPCC SRES background scenarios as well as of the IIASA modeling framework used in this study. Chapter 3 presents more detail on the assumptions underlying the three IPCC SRES background scenarios that serve as baselines for the subsequent analysis of climate stabilization targets. Critical input assumptions in terms of demographic, economic, and technological development, as well as in terms of constraints on resource availability and additional constraints on the availability of zero-carbon options that differ from the IPCC SRES and TAR reports (“WBGU constraints”) are outlined. Chapter 4 presents the climate stabilization scenarios in more detail, outlining the various atmospheric CO_2 concentration targets assumed as well as the regional allocation criteria for emission entitlements suggested by the study sponsor WBGU. The Chapter continues with an analysis of the different emissions and climate change implications of the scenarios as well of the magnitude and type of emission reduction measures suggested by the different scenarios modeled, including issues of international trade in carbon emission permits and an assessment of the costs and the macroeconomic impacts of emission reductions and trade of the climate stabilization scenarios compared with the (unconstrained) modified IPCC SRES background scenarios. Finally, Chapter 5 concludes, highlighting in particular robust findings from the analysis performed here as well as important limitations embedded in the study design and methodology deployed.

2 Methodology

2.1 IPCC Emission Scenarios and the SRES Process

There are more than 500 global emissions scenarios in the literature (Morita and Lee, 1998). They are the main tools for assessing future anthropogenic climate change, possible impacts on human- and ecosystems, and alternative response strategies and policies such as mitigation and adaptation. It is for these reasons that emissions scenarios constitute an important component of the IPCC assessments. The first set of three emissions scenarios was developed by the IPCC in 1990 (Houghton *et al.,* 1990) and the second set of six in 1992 (Leggett *et al.,* 1992; Pepper *et al.,* 1992). The main purpose of the 1990 scenarios was to serve as input for climate models. The second set of six so-called IS92 scenarios were developed by an integrated model and were published two years later. They covered a wide range of main driving forces and emissions outcomes. The IS92 scenarios and especially the central variant IS92a were among the most widely used in the literature and have been reproduced by many of the global energy and emissions models.

In 1994 the IPCC formally evaluated the 1992 scenario set (Alcamo *et al.,* 1995) and, in 1996, based on this review and its findings, it initiated the effort that resulted in a new set of 40 scenarios by six different modeling groups published as IPCC Special Report on Emissions Scenarios (SRES, Nakicenovic *et al*., 2000). This new set of emissions scenarios was developed for use in future IPCC assessments and by wider scientific and policymaking communities. During Third Assessment Report (TAR, 2001) of the IPCC 80 so-called Post-SRES CO_2 stabilization scenarios were developed by nine modeling groups based on 40 SRES baseline scenarios. The Post-SRES scenarios stabilize CO_2 concentrations at various levels ranging from 450 to 750 ppmv by around 2150, half a century later than assumed in this study.

SRES scenarios span 5th to 95th percentile of most important driving forces and GHG emissions ranges from 1990 to 2100 of some 500 scenarios in the literature (that were assembled into a unique database as part of the SRES scenario literature review, see Morita and Lee, 1998). SRES scenarios are based on four narrative storylines developed by the writing team based on the extensive review of quantitative and descriptive scenarios in the literature. Climate change policies were not considered in any of the SRES scenarios as specified by the SRES terms of reference while CO_2-mitigation policies and measures were included explicitly in the Post-SRES CO_2-stabilization scenarios. The four SRES storylines were quantified by six alternative integrated assessment models (IAM) resulting in 40 SRES reference scenarios and by nine IAMs resulting in 80 Post-SRES CO_2-stabilization scenarios. The scenarios are reported for four “macro” world regions but individual models provide more detailed information at spatial resolutions of dozen and more world regions.

The emissions profiles of the SRES and Post-SRES scenarios have provided inputs for GCMs and simplified models of climate change. They contain information, such as the level of economic activities, rates of technological change, and demographic developments in different world regions, required to assess climate-change impacts and vulnerabilities, adaptation strategies and policies. The same kind of information, in conjunction with emissions trajectories, can serve as a benchmark for the evaluation of alternative mitigation measures and policies. Post-SRES scenarios provide information on the mitigation efforts necessary to stabilize CO_2 atmospheric concentrations at alternative levels. Finally, the SRES scenarios can provide a common basis and an integrative element across the three working groups for the IPCC Fourth Assessment Report (AR4). In this study three of the 40 SRES scenarios (SRES-A1, SRES-B1, and SRES-B2) are used a background scenarios for achieving CO_2 atmospheric concentrations stabilization at a very low levels of 400 to 450 ppmv through a very limited and restricted number of mitigation measures and options.

2.2 Modeling Framework

The principal models and data sets used to develop the scenario projections for the IPCC SRES and TAR are shown in Figure 2.1. They are the Scenario Generator (Nakicenovic *et a1.*, 1998a), the bottom-up systems engineering model MESSAGE IV (Messner and Strubegger, 1995), the top-down macroeconomic model MACRO (Messner and Schrattenholzer, 2000), the climate impact model MAGICC (Wigley and Raper, 1997 and 2002; Hulme *et al.*, 2000), and several databases, most importantly the energy technology database CO2DB (Strubegger *et al.*, 1999). Each is described in turn. For further details on the modeling framework see Riahi and Roehrl (2000a,b).

For the purpose of this study and the development scenarios presented in Chapter 3 and 4, a subset of the above models was used. Specifically, MESSAGE was adapted for the estimation of detailed regional energy system development paths consistent with the specifications and constraints defined by the WBGU. In addition, the macroeconomic model MACRO was applied to assess the economic impact and price-induced changes of energy demand due to carbon abatement policies. Climate indicators, such as the scenario’s atmospheric CO_2 concentrations, temperature change, and sea level rise, were calculated with the newest version of the MAGICC model (version 3.0) using an updated parametrization to derive consistent climate projections with the IPCC TAR (2001). The models are used in an iterative fashion, which permits the endogenization of internally consistent energy-economic-climate indicators from a macroecomomic and energy systems perspective.

We shall now describe each of the models.

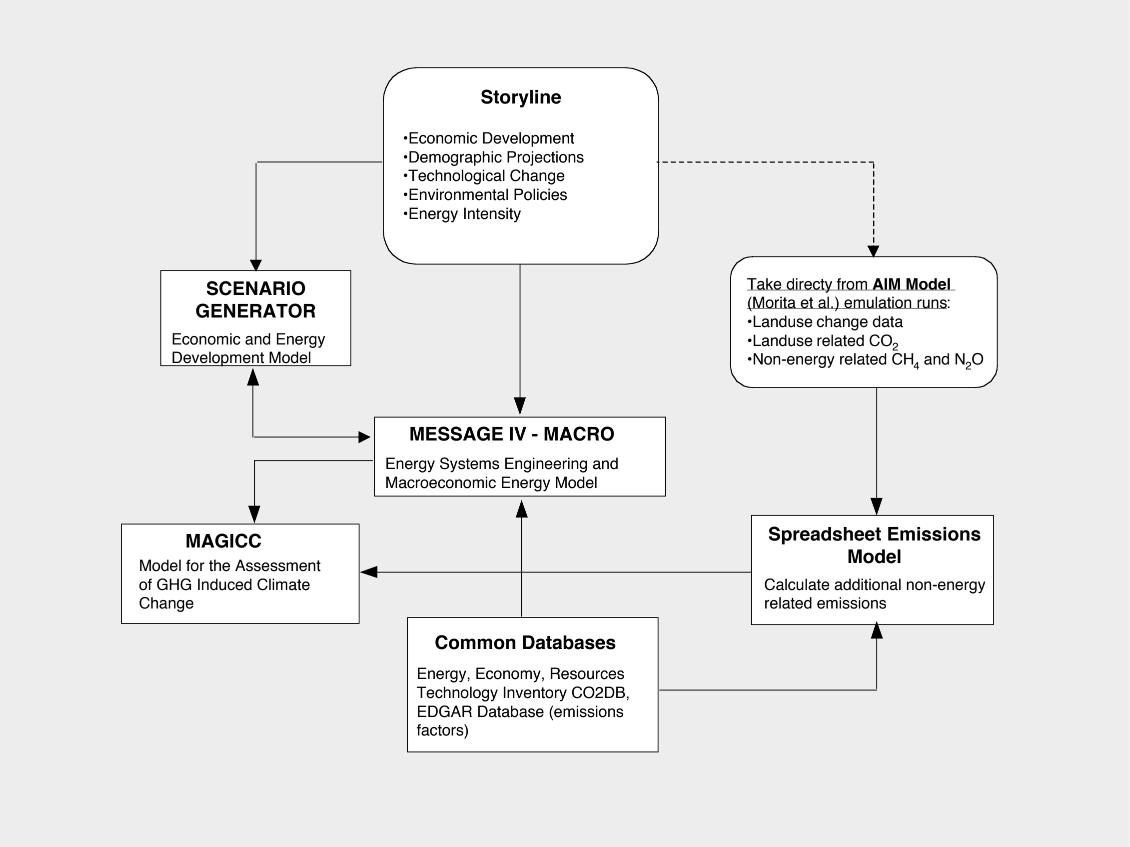

Figure 2.1: The IIASA modeling framework used for the IIASA-SRES scenarios, including the Scenario Generator, MESSAGE IV, MACRO, and associated databases. The climate impact model MAGICC was used in addition to calculate GHG concentrations and changes in radiative forcing, global temperature, and sea level rise.

2.2.1 The Scenario Generator

The Scenario Generator (SG, Nakicenovic *et al.*, 1998a, and 1998b) is a simulation model to help formulate scenarios of economic and energy development for eleven world regions analyzed by MESSAGE IV. Its main objective is to allow the scenario formulation and documentation of key scenario assumptions, and to provide common, consistent input data for MESSAGE IV and MACRO.

Within the SG there are, first, consistent sets of economic and energy data for the base year 1990 and 2000, plus time series of such data for prior years. Second, the SG contains a set of regression equations estimated using the economic and energy data sets. These equations represent key relationships between economic and energy development, based on empirical data, that can be used selectively in formulating particular scenarios. To allow adjustments for different storylines and variants, all-important variables are formulated so that a user can overwrite the values suggested by the equations of the SG.

Inputs to the SG are future population trajectories for eleven world regions used by MESSAGE IV plus key parameters determining regional per capita GDP growth. The SG first calculates growth rates of total GDP for each world region. Second, it calculates total final energy trajectories for each region by combining the population and per capita GDP growth trajectories with final energy intensity profiles based on the SG's set of empirically derived equations. The resulting final energy demands are then disaggregated, again based on combining regional per capita income growth with the SG's set of empirically derived equations, into the six demand sectors used by MESSAGE IV and listed below. In the list, "specific" energy demands are those that require electricity (or its substitutes such as, in the long term, hydrogen). "Non-specific" energy demands are mainly thermal requirements that can be fulfilled by any energy form.

- industrial specific
- industrial non-specific
- residential/commercial specific
- residential/commercial non-specific
- transportation
- non-commercial (e.g, fuelwood)

2.2.2 The Systems Engineering Model MESSAGE IV

MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) is a systems-engineering optimization model used for medium- to long-term energy system planning, energy policy analysis, and scenario development (Messner and Strubegger, 1995). The model provides a framework for representing an energy system with all its interdependencies from resource extraction, imports and exports, conversion, transport, and distribution, to the provision of energy end-use services such as light, space conditioning, industrial production processes, and transportation. The model's current version, MESSAGE IV, provides information on the utilization of domestic resources, energy imports and exports and trade-related monetary flows, investment requirements, the types of production or conversion technologies selected (technology substitution), pollutant emissions, inter-fuel substitution processes, as well as temporal trajectories for primary, secondary, final, and useful energy.

The degree of technological detail in the representation of an energy system is flexible and depends on the geographical and temporal scope of the problem being analyzed. A typical model application is constructed by specifying performance characteristics of a set of technologies and defining a Reference Energy System (RES) that includes all the possible energy chains that the model can make use of. In the course of a model run MESSAGE IV will then determine how much of the available technologies and resources are actually used to satisfy a particular end-use demand, subject to various constraints, while minimizing total discounted energy system costs. An illustration of the MESSAGE Reference Energy System is given in Figure 2.2.

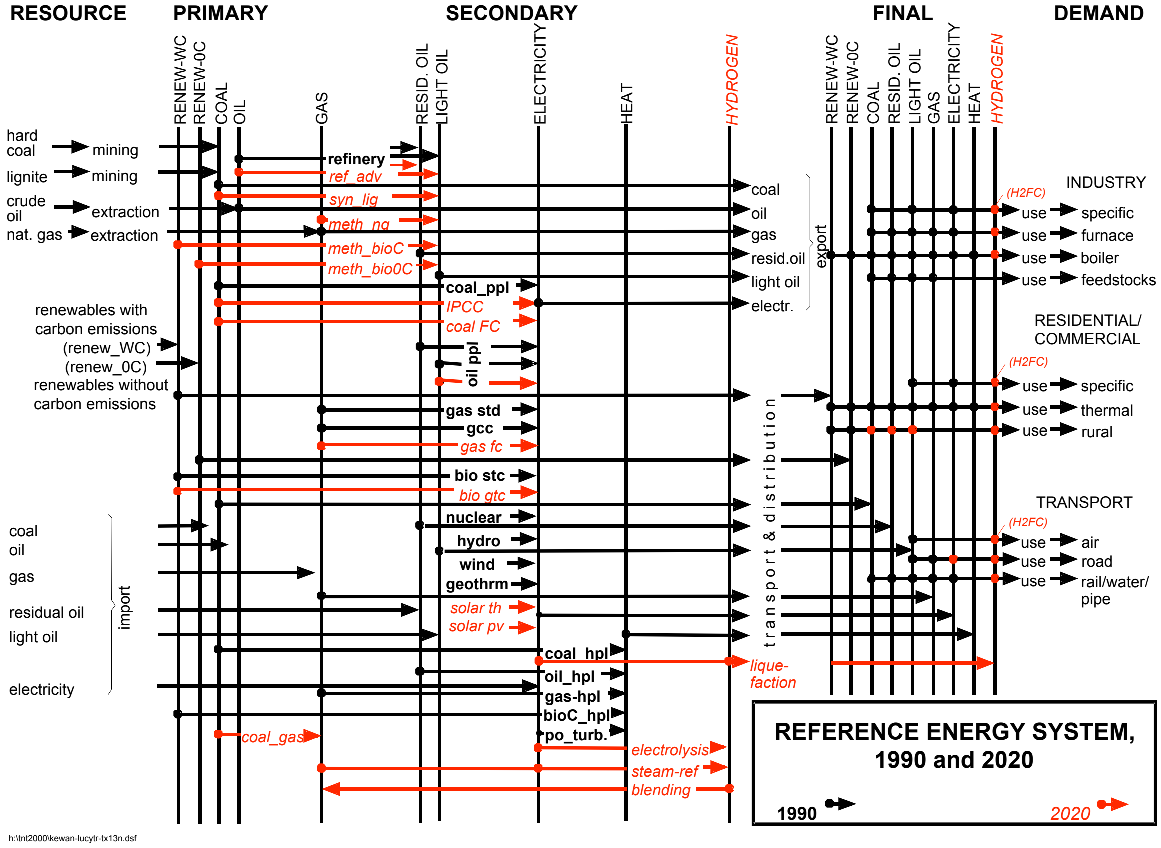

Figure 2.2: Schematic diagram of the basic energy system structure in the MESSAGE model.

2.2.3 The Macroeconomic Model MACRO

MACRO is a top-down macroeconomic model (Manne and Richels, 1992, Messner and Schrattenholzer, 2000). Its objective function is the total discounted utility of a single representative producer-consumer. The maximization of this utility function determines a sequence of optimal savings, investment, and consumption decisions. In turn, savings and investment determine the capital stock. The capital stock, available labor, and energy inputs determine the total output of an economy according to a nested constant elasticity of substitution (CES) production function. Energy demand in two categories (electricity and non-electric energy) is determined within the model, consistent with the development of energy prices and the energy intensity of GDP.

The main determinants of energy demand are the *reference* GDP growth input into the model and the development of the overall energy intensity of GDP. Energy supply is represented by two quadratic cost functions, one for each of MACRO's two demand categories, and is determined so as to minimize costs. MACRO's outputs include internally consistent projections of world and regional *realized* GDP (i.e., taking into account the feedback that changing energy and other costs have on economic growth) including the disaggregation of total production into macroeconomic investment, overall consumption, and energy costs.

2.2.4 Iterating MESSAGE with MACRO

Linking MACRO with MESSAGE permits the estimation of internally consistent projections of energy prices and energy systems costs – derived from a detailed systems engineering model (MESSAGE) – with economic growth and energy demand projections obtained from a macroeconomic model (MACRO). The scenario results are calculated in an iterative fashion (see Figure 2.3). As the initial step MESSAGE calculates energy prices and system costs for a given energy demand, and passes this information to MACRO. MACRO then calculates the optimal allocation of the production factors (capital, labor and energy) and the imputed effect on GDP and energy demand. The corrected demand from MACRO is returned to MESSAGE, which initiates again the calculation of the energy prices and system costs. This iteration ends as soon as convergence between the two models is achieved.

This approach is particularly important in the case of policy scenarios that assume trading of emissions permits, since the associated monetary transfers have a significant impact on the regional economic development. In the WBGU scenarios this effect is taken into account by adding the costs from carbon trading to the energy systems costs of MESSAGE.[2] MACRO uses the corrected systems costs as an input and calculates the implied effect on GDP and the total economic production by adjusting the optimal allocation of the production factors (capital, labor, and energy). As a result scenarios are obtained, where the prices of energy and carbon as well as the price-induced changes of GDP and energy demand are endogenized and internally fully consistent.

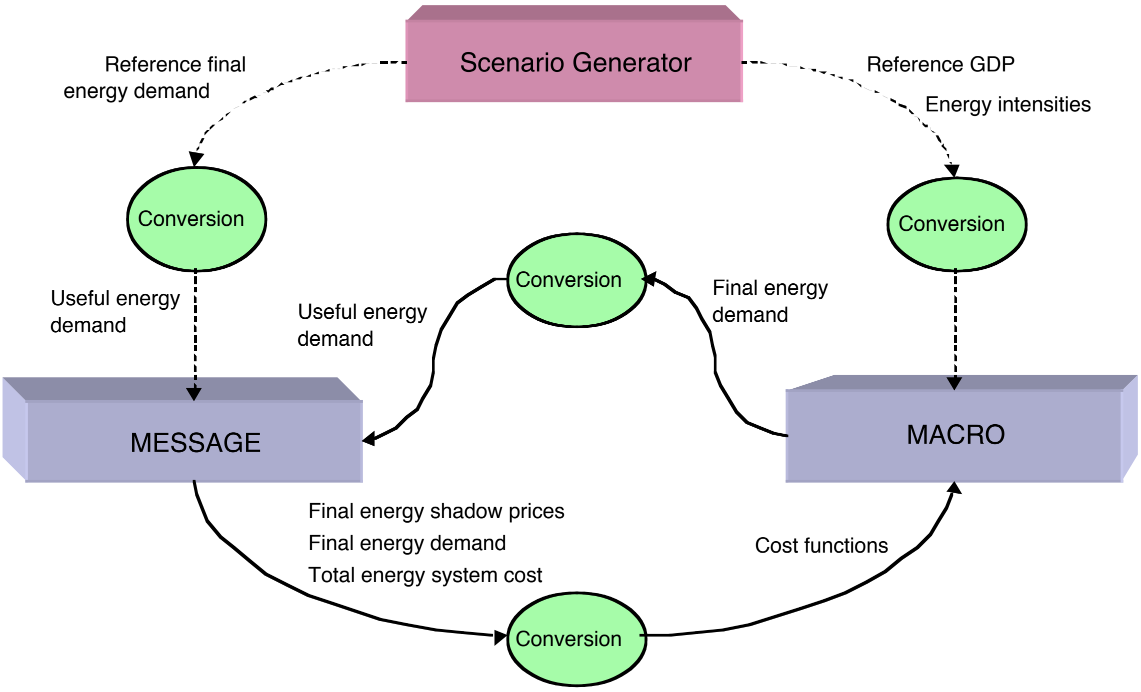

Figure 2.3: Schematic illustration of MESSAGE-MACRO iterations.

2.2.5 The Climate Change Model MAGICC

To estimate aggregate climate impacts of the scenarios Version 3.0 of the climate change model MAGICC (Model to Assess Greenhouse-gas Induced Climate Change: Wigley and Raper, 2002) was used. MAGICC includes a carbon cycle model that relates atmospheric inputs (emissions) and outputs (physical and chemical sink processes) to changes in the atmospheric carbon concentration. It uses carbon dioxide (CO_2), methane (CH_4), sulfur dioxide (SO_2), and nitrogen oxide (NO_x) energy-related emissions from MESSAGE together with emission profiles for other greenhouse

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[2] In the case a region gains revenues from carbon trading, they are subtracted from the respective energy systems costs, reducing thus energy costs, rising regional GDP growth.

gases and non-energy related activities as described in SRES.[3] The model estimates net carbon flows and atmospheric CO_2 concentrations, changes in radiative forcing and temperature relative to 1990, and sea level rise.

3 Baseline Scenarios

3.1 Introduction to IPCC SRES Baseline Scenarios

The three GHG stabilization scenarios presented in this study are based on the SRES background scenarios. This section reviews the SRES baseline scenarios. SRES background or "reference" scenarios provide 40 GHG emissions baselines based on different future worldviews. During the IPCC Third Assessment Report (TAR), SRES scenarios served as background scenarios to develop the 80 Post-SRES stabilization scenarios. The approach in this study is similar in the sense that three of the 40 SRES scenarios provide the background information for developing the GHG stabilization scenarios for the IPCC TAR. (The main difference to this study is that the TAR scenarios stabilize CO_2 concentrations at levels ranging from 450 to 750 ppmv by around 2150, whereas in this study, the lowest range of 400 to 450 ppmv is chosen for all GHGs in conjunction with half-a-century earlier stabilization of concentrations.)

The basic approach of the SRES writing team was to construct scenarios that were both qualitative and quantitative (SRES, Nakicenovic *et al.*, 2000). The process involved first the formulation of the qualitative scenario characteristics in the form of four narrative storylines and then their quantification by six different modelling approaches. The qualitative description gives background information about the global setting of the scenarios, which can be used, like in this study, to assess the capability of society to adapt to and mitigate climate change, or for linking the emission scenarios with sustainability and equity issues. The quantitative description of emission scenarios can be used as input to models for computing the future extent of climate change, and for assessing strategies to reduce emissions. Again, they are use in the same way in this study, first a simple climate model (MAGICC) is used to assess future GHG concentrations and climate change implication and than the IIASA integrated modelling framework was used to (iteratively) achieve the concentrations stabilization at very low levels of 400 to 450 ppmv CO_2 equivalent by 2100 through a very restricted set of mitigation measures and options.

The relation between qualitative and quantitative scenarios can be characterized in terms of Figure 3.1.

The SRES writing team developed four scenario "families", because an even number helps to avoid the impression that there is a "central" or "most likely" case. Box 3.1 provides an explanation of terminology used in SRES and Figure 3.2 illustrates this scenario terminology schematically. There are four scenario families that are branch out into 6 scenario groups that include altogether 40 emissions scenarios. The scenarios cover a wide range – but not all possible futures. In particular, there are no "global disaster" scenarios where the poor parts of the world become even poorer or where catastrophic events endanger human survival in general. None of the SRES scenarios include new explicit climate policies such as the fulfilment of Kyoto Protocol.

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[3] For the stabilization scenarios the emission profiles for other GHGs than CO_2 were obtained from equivalent stabilization scenarios based on SRES as reported in Swart et al., 2001, and in Rao and Riahi, 2003. These non-energy, non-industry GHGs do not form part of the cost minimization model used for the stabilization scenarios here, but are exogenous study input assumptions.

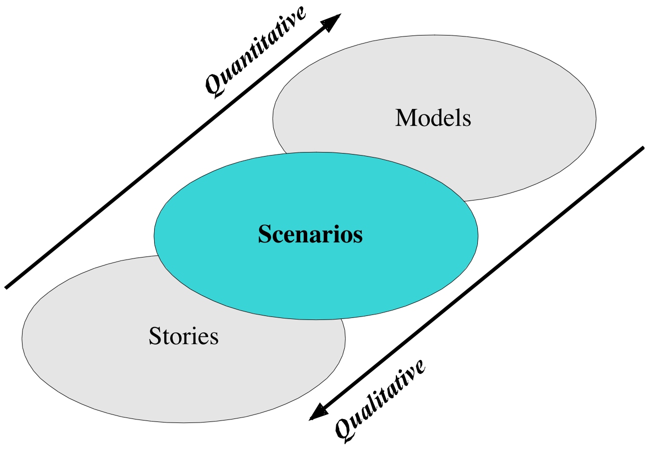

Figure 3.1: Schematic illustration of alternative scenario formulations ranging from narrative storylines to quantitative formal models (source: Nakicenovic et al., 2000).

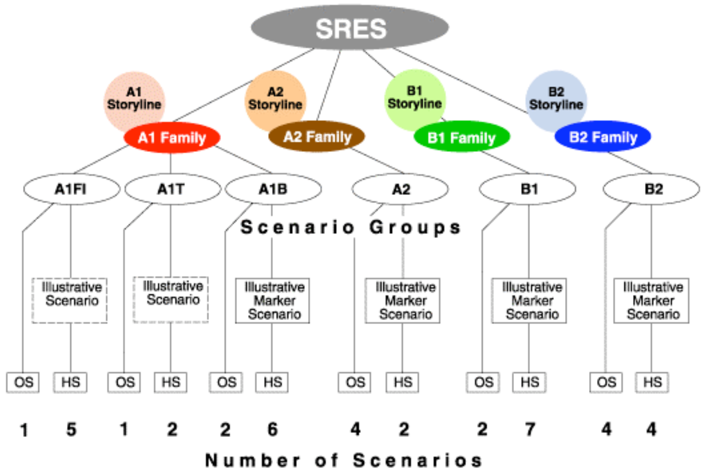

Figure 3.2: Schematic illustration of SRES scenarios. The set of scenarios consists of the four scenario families A1, A2, B1, and B2. Each family consists of a number of scenarios, some of which have "harmonized" driving forces and share the same prespecified population and gross world product (a few that also share common final energy trajectories are called "fully harmonized"). These are marked as "HS" for harmonized scenarios. One of the harmonized scenarios, originally posted on the open-process web site, is called a "marker scenario." All other scenarios of the same family based on the quantification of the storyline chosen by the modeling team are marked as "OS." Six modeling groups developed the set of 40 emissions scenarios. The GHG and SO_2 emissions of the scenarios were standardized to share the same data for 1990 and 2000 on request of the user communities. The time-dependent standardized emissions were also translated into geographic distributions.

Box 3.1: IPCC SRES Scenario Terminology (Source: SRES, Nakicenovic *et al.*, 2000).

Model:	a formal representation of a system that allows quantification of relevant system variables.
Storyline:	a narrative description of a scenario (or a family of scenarios) highlighting the main scenario characteristics, relationships between key driving forces, and the dynamics of the scenarios.
Scenario:	a description of a potential future, based on a clear logic and a quantified storyline.
Family:	scenarios that have a similar demographic, societal, economic, and technical-change storyline. Four scenario families comprise the SRES: A1, A2, B1, and B2.
Group:	scenarios within a family that reflect a variation of the storyline. The A1 scenario family includes three groups designated by A1T, A1FI, and A1B that explore alternative structures of future energy systems. The other three scenario families consist of one group each.
Category:	scenarios are grouped into four categories of cumulative CO_2 emissions between 1990 and 2100: low, medium-low, medium-high, and high emissions. Each category contains scenarios with a range of different driving forces yet similar cumulative emissions.
Marker:	a scenario that was originally posted on the SRES website to represent a given scenario family. A marker is not necessarily the median or mean scenario.
Illustrative:	a scenario that is illustrative for each of the six scenario groups reflected in the Summary for Policymakers of this report. They include four revised "scenario markers" for the scenario groups A1B, A2, B1, and B2, and two additional illustrative scenarios for the A1FI and AIT groups. See also “(Scenario) Groups” and “(Scenario) Markers”.
Harmonized:	harmonized scenarios within a family share common assumptions for global population and GDP while fully harmonized scenarios are within 5% of the population projections specified for the respective marker scenario, within 10% of the GDP and within 10% of the marker scenario’s final energy consumption.
Standardized:	emissions for 1990 and 2000 are indexed to have the same values.
Other scenarios:	scenarios that are not harmonized.

Each family has a unifying theme in the form of a “storyline” or narrative that describes future demographic, social, economic, technological, and policy trends. Four storylines were developed by the whole writing team that identified driving forces, key uncertainties, possible scenario families, and their logic. Six global modelling teams then quantified the storylines. The quantification consisted of first translating the storylines into a set of quantitative assumptions about the driving forces of emissions (for example, rates of change of population and size of the economy and rates of technological change). Next, these assumptions were input to six integrated, global models that computed the emissions of GHGs and sulphur dioxide (SO_2). As a result, a total of 40 scenarios were produced for the four storylines. The large number of alternative scenarios showed that a single storyline could lead to a large number of feasible emission pathways (Nakicenovic *et al.*, 2000; Morita *et al.*, 2001).

In all, six models were used to generate the 40 scenarios that comprise the four scenario families**.** Six of these scenarios, which should be considered equally sound, were chosen to illustrate the whole set of scenarios. They span a wide range of uncertainty, as required by the SRES Terms of Reference. These encompass four combinations of demographic change, social and economic development, and broad technological developments, corresponding to the four families (A1, A2, B1, B2), each with an illustrative “marker” scenario. Two of the scenario groups of the A1 family (A1FI, A1T) explicitly explore energy technology developments, alternative to the “balanced” A1B group, holding the other driving forces constant, each with an illustrative scenario. Rapid growth leads to high capital turnover rates, which means that early small differences among scenarios can lead to a large divergence by 2100. Therefore, the A1 family, which has the highest rates of technological change and economic development, was selected to show this effect.

To provide a scientific foundation for the scenarios, the writing team extensively reviewed and evaluated the scenario literature. Results of the review were published in the scientific literature (Alcamo and Nakicenovic, 1998), and made available to the scientific community in the form of an Internet scenario database (Morita and Lee, 1998). The background research by the six modelling teams for developing the 40 scenarios was also published in the scientific literature (Nakicenovic, 2000).

3.2 A short description of the SRES Scenarios

3.2.1 Introduction

Ranges of possible future emissions and their driving forces are very large so that there are an infinite number of alternative futures to explore. Since there is no agreement on how the future will unfold, the SRES tried to sharpen the view of alternatives by assuming that individual scenarios have diverging tendencies – one emphasizes stronger economic values, the other stronger environmental values; one assumes increasing globalisation, the other increasing rationalization. Combining these choices yielded four different scenario families as illustrated schematically in Figure 3.3. This two-dimensional representation of the main SRES scenario characteristics is an oversimplification (Nakicenovic *et al*., 2000). It is shown just as an illustration. In fact, to be accurate, the space would need to be multi-dimensional, listing other scenario developments in many different social, economic, technological, environmental, and policy dimensions.

The titles of the four scenario storylines and families have been kept simple: A1, A2, B1, and B2. There is no particular order among the storylines; they are listed in alphabetical and numerical order:

- The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B).[4]

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[4] Balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end-use technologies.

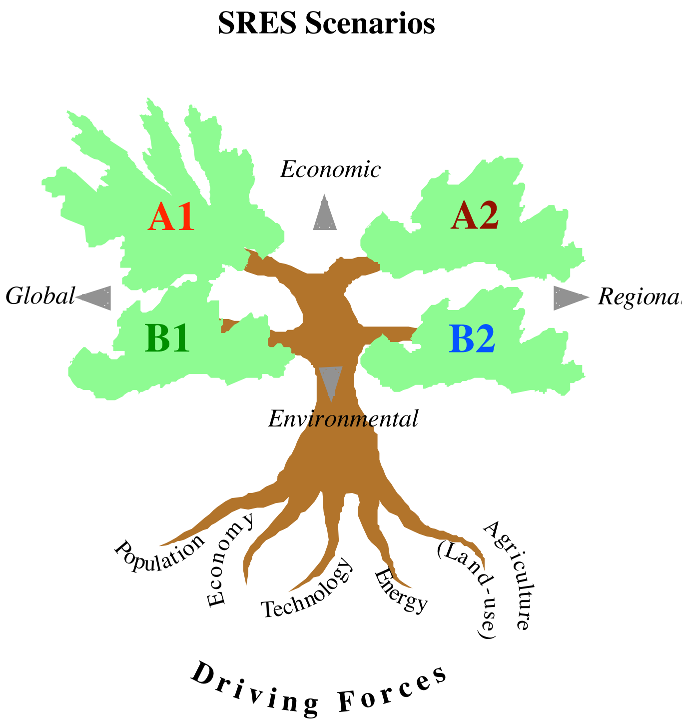

Figure 3.3: Schematic illustration of SRES scenarios. The four scenario "families" are shown, very simplistically, for illustrative purposes, as branches of a two-dimensional tree. The two dimensions shown indicate global and regional scenario orientation, and development and environmental orientation, respectively. In reality, the four scenarios share a space of a much higher dimensionality given the numerous driving forces and other assumptions needed to define any given scenario in a particular modelling approach. The schematic diagram illustrates that the scenarios build on the main driving forces of GHG emissions. Each scenario family is based on a common specification of some of the main driving forces. Source: SRES, Nakicenovic et al., 2000.

- The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.
- The B1 storyline and scenario family describes a convergent world with the same global population that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.
- The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with a continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse

technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

In all, six models were used to generate the 40 scenarios that comprise the four scenario families. They are listed in Box 3.2. These six models are representative of emissions scenario modelling approaches and different integrated assessment frameworks in the literature, and include so-called top-down and bottom-up models.

Box 3.2: Models used to generate the SRES scenarios.

- Asian Pacific Integrated Model (AIM) from the National Institute of Environmental Studies in Japan (Morita *et al*., 1994);
- Atmospheric Stabilization Framework Model (ASF) from ICF Consulting in the USA (Lashof and Tirpak, 1990; Pepper *et al.,* 1992, and 1998; Sankovski *et al*., 2000);
- Integrated Model to Assess the Greenhouse Effect (IMAGE) from the National Institute for Public Health and Environmental Hygiene (RIVM) (Alcamo *et al.,* 1998; de Vries *et al*., 1994, 1999, 2000), used in connection with the Dutch Bureau for Economic Policy Analysis (CPB) WorldScan model (de Jong and Zalm, 1991), the Netherlands;
- Multiregional Approach for Resource and Industry Allocation (MARIA) from the Science University of Tokyo in Japan (Mori and Takahashi, 1999; Mori, 2000);
- Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE) from the International Institute of Applied Systems Analysis (IIASA) in Austria (Messner and Strubegger, 1995; Riahi and Roehrl, 2000a); and the
- Mini Climate Assessment Model (MiniCAM) from the Pacific Northwest National Laboratory (PNNL) in the USA (Edmonds *et al*., 1994, 1996a and 1996b).

3.2.2 Emissions and Other Results of the SRES Scenarios

Figure 3.4 illustrates the range of global energy-related and industrial CO_2 emissions for the 40 SRES scenarios against the background of all the 500 emissions scenarios from the literature documented in the SRES scenario database. The six SRES scenario groups are represented by the six illustrative scenarios. Figure 3.4 also shows a range of emissions of the six scenario groups next to each of the six illustrative scenarios.

Figure 3.4 shows that the four marker and two illustrative scenarios by themselves cover a large portion of the overall scenario distribution. This is one of the reasons that the SRES Writing Team recommended the use of all four marker and two illustrative scenarios in future assessments. Together, they cover most of the uncertainty of future emissions, both with respect to the scenarios in the literature and the full SRES scenario set. Figure 3.4 also shows that they are not necessarily close to the median of the scenario family because of the nature of the selection process. For example, A2 and B1 are at the upper and lower bounds of their scenario families, respectively. The range of global energy-related and industrial CO_2 emissions for the six illustrative SRES scenarios is generally somewhat lower than the range of the IPCC IS92 scenarios (Leggett *et al*., 1992; Pepper *et al*., 1992). Adding the other 34 SRES scenarios increases the covered emissions range. Jointly, the SRES scenarios cover the relevant range of global emissions, from the 95th percentile at the high end of the distribution all the way down to very low emissions just above the 5th percentile of the distribution. Thus, they only exclude the most extreme emissions scenarios found in the literature – those situated out in the tails of the distribution. What is perhaps more important is that each of the four scenario families covers a sizable part of this distribution, implying that a similar quantification of driving forces can lead to a wide range of future emissions. More specifically, a given combination of the main driving forces is not sufficient to uniquely determine a future emission path. There are too many uncertainties. The fact that each of the scenario families covers a substantial part of the literature range also leads to an overlap in the emissions ranges of the four families. This implies that a given level of future emissions can arise from very different combinations of driving forces. This result is of fundamental importance for assessments of climate change impacts and possible mitigation and adaptation strategies.

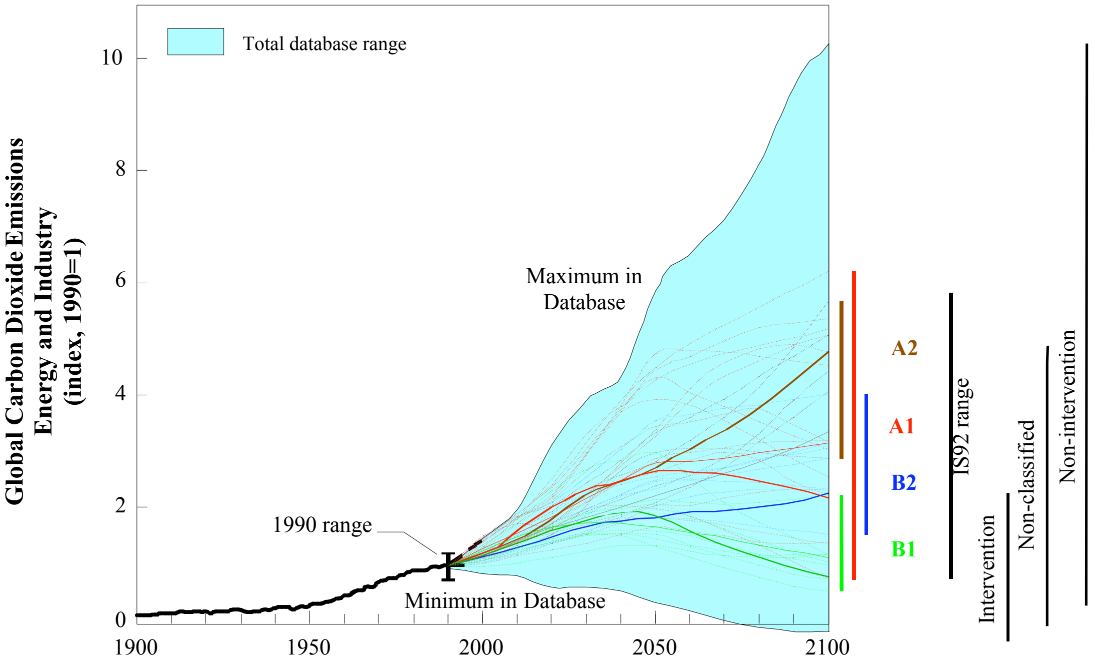

Figure 3.4: Global CO_2 emissions from energy and industry, historical development from 1900 to 1990 and in 40 SRES scenarios from 1990 to 2100, shown as an index (1990 = 1). The range is large in the base year 1990, as indicated by an "error" bar, but is excluded from the indexed future emissions paths. The dashed time-paths depict individual SRES scenarios and the blue shaded area the range of scenarios from the literature (as documented in the SRES database). The median (50th), 5th, and 95th percentiles of the frequency distribution are shown. The statistics associated with the distribution of scenarios do not imply probability of occurrence (e.g., the frequency distribution of the scenarios in the literature may be influenced by the use of IS92a as a reference for many subsequent studies). The 40 SRES scenarios are classified into six groups. Jointly the scenarios span most of the range of the scenarios in the literature. The emissions profiles are dynamic, ranging from continuous increases to those that curve through a maximum and then decline. The coloured vertical bars indicate the range of the four SRES scenario families in 2100. Also shown as vertical bars on the right are the ranges of emissions in 2100 of IS92 scenarios, and of scenarios from the literature that apparently include additional climate initiatives (designated as "intervention" scenarios emissions range), those that do not ("non-intervention"), and those that cannot be assigned to either of these two categories ("non-classified").

An important feature of the SRES scenarios obtained using the SAR methodology is that their overall radiative forcing is higher than the IS92 range despite comparatively lower GHG emissions (Wigley and Raper, 1992; Wigley *et al.*, 1994; Houghton *et al.*, 1996; Smith *et al.*, 2000; IPCC, 2001). This is owing to the loss of sulphur-induced cooling during the second half of the 21st century. On one hand, the reduction in global sulphur emissions reduces the role of sulphate aerosols in determining future climate, and therefore reduces one aspect of uncertainty about future climate change (because the precise forcing effect of sulphate aerosols is highly uncertain). On the other hand, uncertainty increases because of the diversity in spatial patterns of SO_2 emissions in the scenarios. Future assessments of possible climate change need to account for these different spatial and temporal dynamics of GHG and sulphur emissions, and they need to cover the whole range of radiative forcing associated with the scenarios.

In summary, the SRES scenarios lead to the following findings:

- Alternative combinations of driving-force variables can lead to similar levels and structure of energy use and land-use patterns, as illustrated by the various scenario groups and scenarios. Hence, even for a given scenario outcome, for example, in terms of GHG emissions, there are alternative combinations and alternative pathways that could lead to that outcome. For instance, significant global changes could result from a scenario of high population growth, even if per capita incomes would rise only modestly, as well as from a scenario in which a rapid demographic transition (low population levels) would coincide with high rates of income growth and affluence.
- Important possibilities for further bifurcations in future development trends exist within one scenario family, even when adopting certain values for important scenario driving force variables to illustrate a particular possible development path.
- Emissions profiles are dynamic across the range of SRES scenarios. They portray trend reversals and indicate possible emissions crossover among different scenarios. They do not represent mere extensions of a continuous increase of GHGs and sulphur emissions into the future. This more complex pattern of future emissions across the range of SRES scenarios reflects the recent scenario literature.
- Describing potential future developments involves inherent ambiguities and uncertainties. One and only one possible development path (as alluded to for instance in concepts such as “business-as-usual scenario”) simply does not exist. And even for each alternative development path described by any given scenario, there are numerous combinations of driving forces and numerical values that can be consistent with a particular scenario description. This particularly applies to the A2 and B2 scenarios that imply a variety of regional development patterns that are wider than in the A1 and B1 scenarios. The numerical precision of any model result should not distract from the basic fact that uncertainty abounds. However, in the opinion of the SRES writing team, the multi-model approach increases the value of the SRES scenario set, since uncertainties in the choice of model input assumptions can be more explicitly separated from the specific model behaviour and related modelling uncertainties.
- Any scenario has subjective elements and is open for various interpretations. While the SRES writing team as a whole has no preference for any of the

scenarios, and has no judgement about the probability or desirability of the scenarios, the open process and reactions to SRES scenarios have shown that individuals and interest groups do have such judgements. This will stimulate an open discussion in the political arena about potential futures and choices that can be made in the context of climate change response. For the scientific community, the SRES scenario exercise has led to the identification of a number of recommendations for future research that can further increase understanding about potential development of socio-economic driving forces and their interactions, and associated GHG emissions.

3.3 WGBU Baseline Scenarios

3.3.1 Introduction to WGBU Scenarios

Three background scenarios are analyzed in this study that are subject a stringent climate stabilization constraints (400 and 450 ppmv stabilization by 2100). They also analyze feasibility and costs of meeting climate stabilization at such low levels under additional constraints on zero-carbon energy technologies and carbon sequestration (referred below as "WBGU constraints").

The three (no-climate-control) base case scenarios are based on the IPCC SRES scenarios: SRES-A1, SRES-B1, and SRES-B2 (that were described above). Scenarios A1 and B1 embrace a "sustainable development" paradigm, with the SRES-A1 scenario focusing of the economic and social dimensions (income growth and disparity reduction) and the SRES-B1 scenario focusing in addition also on the environmental dimension (resource conservation and control of traditional pollutants with exception of GHGs) of the "three pillars" (social, economic, environmental) of sustainable development. Furthermore, the original SRES scenario sets contained a number of scenario groups embedded within the overall scenario family A1, essentially depending on rates and direction of technological change spanning all the extremes from fossil fuel intensive (SRES A1FI) to low- and zero-emission technology intensive (A1T). For the purposes of this study, the SRES A1T scenario was adopted as background scenario as it was structurally quite close to the B1 scenario (albeit at much higher levels of energy demand) in order to explore some degree of uncertainty that may surround a sustainable development scenario. In other words for the purposes of this study both SRES scenarios A1T as well as B1 are considered describing similar overall global developments: a transition towards sustainability. In this study, the primary focus is on climate change issues. Hence these two "non-intervention" scenarios are analyzed for two levels of climate stabilization: 450 ppmv (in case of the A1T scenario) and 400 ppmv in case of the B1 scenario much in line to similar modeling exercises performed within IPCC TAR.

A third SRES scenario (B2) is also analyzed, primarily as a means of comparison for the two other scenarios. The more intermediate, "dynamics as usual" scenario SRES-B2 provides a contrast of a baseline that provides less favorable conditions for climate policies compared to its sustainable development scenario counterparts A1T and B1. For this scenario we also assume a stringent climate stabilization target of 400 ppmv – even if this very ambitious target may not necessarily be consistent with the more cautious geopolitical, economic and technologic outlook described in the SRES-B2 background scenario storyline.

3.3.2 Input Assumptions

In the following sections important input assumptions, characterizing the three background scenarios and their corresponding policy scenarios are described. In-as-far as the scenarios have retained the original IPCC SRES assumptions they are extensively documented in the literature and Internet (e.g., see Nakicenovic *et al.*, 2000)[5]. Instead, the most important features of the scenario input assumptions are summarized, and documented in tabular form with an indication where they depart from the original IPCC SRES numbers. In addition, some of numerical assumptions identical to SRES are also reproduced, as is the case for the GDP scenarios, because they are important for the understanding of the quantitative study results presented in Chapter 4.

Population

The three background scenarios are based on two population projections. One (underlying the SRES-B2) scenario is a medium population projection in which global fertility patterns are assumed to converge to replacement level by the end of the 21st century (based on the corresponding UN Medium projection). World population continues to rise in order to stabilize at a level of approximately 10 billion people by 2100 (and to remain at that level thereafter). The two sustainable development scenarios share the same, low population projection. In this (sub-replacement fertility) scenario world population would peak below 9 billion people by the mid 21st century in order to decline to some 7 billion by 2100 (declining further thereafter). It should be noted that this choice of base case scenarios excludes the possibility of high population growth from the analysis reported here.

Economic Growth

For reasons of consistency and comparability to both IPCC SRES and TAR, the original SRES GDP growth scenarios were used for the three baseline scenarios in this study (see Table 3.1).[6] These original economic development paths are not reached due to the costs of stabilization, so that the resulting rates of economic development are lower in the WGBU stabilization scenarios. In order to ease the subsequent comparison of the GDP "losses" associated with the WGBU climate stabilization scenarios, we replicate the corresponding SRES GDP input assumptions for both measures of economic growth reported in SRES: GDP at market exchange rates (mer) and GDP expressed at purchasing power parities (ppp).

It should be noted that two out of the three WGBU scenarios adopt a normative and optimistic outlook on the development catch-up of developing countries. This is an outcome of the original IPCC SRES scenario characteristics that serve as baselines for the WGBU scenarios. As such these scenarios not only reflect fulfillment of the aspirations of the economic dimensions of sustainable development, but are also in terms of resource and technology availability rather optimistic, providing a positive

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[5] In addition to extensive documentation of SRES scenarios in the public domain, all detailed scenario assumptions and results have been provided in electronic form to WBGU. Thus, there is no need to reproduce this statistical information extensively here. Instead, here we focus on the main driving forces and developments in the three scenarios.

[6] Strictly speaking the GDP growth in the WBGU scenarios A1T and B1 would be slightly lower than in the original SRES scenarios, as the additional WBGU constraints imposed on these scenarios would lead to some increases in energy prices, thus somewhat reducing energy demand and GDP growth. Quantitative model simulations have however indicated that this macro-economic effect would be so small as to be insignificant over the time period and magnitude of the GDP growth reported here.

and receptive environment for the implementation of climate stabilization policies. Scenario B2 is more cautious than the two “ideal worlds” scenario counterparts, but even in this scenario, the development aspirations of the South are largely fulfilled even if occurring at a slower pace and with greater disparities to the industrialized countries. It should be noted, that none of the scenarios analyzed here considers the possibility of a development failure or of widening North-South development gaps.

Table 3.1 GDP scenarios 1990 to 2100 expressed at market exchange rates (mer) and purchasing power parities (ppp) for the three IPCC SRES scenarios analyzed in this study. In trillion US$(1990).

		1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
A1													
World	mex	20.9	26.7	37.9	56.5	89.1	135.2	181.3	247.6	313.8	383.3	455.9	528.5
	ppp	25.7	33.3	47.1	66.6	96.6	138.9	181.0	240.7	304.2	372.2	443.0	513.9
OECD90	mex	16.4	20.5	25.3	31.0	38.0	46.1	54.1	65.5	76.9	90.3	105.7	121.1
	ppp	14.1	17.7	21.8	26.9	33.0	40.1	47.2	57.2	67.3	79.2	92.9	106.6
REF	mex	1.1	0.8	1.5	2.9	5.3	8.8	12.4	16.2	20.0	24.4	29.3	34.2
	ppp	2.6	2.2	3.1	4.3	6.0	8.8	12.4	16.2	20.0	24.4	29.3	34.2
ASIA	mex	1.5	2.7	5.8	12.3	26.2	44.5	62.7	91.9	121.0	150.0	178.6	207.3
	ppp	5.3	8.2	13.5	21.6	35.2	51.8	67.5	93.3	121.0	150.0	178.6	207.3
ALM	mex	1.9	2.7	5.3	10.3	19.5	35.8	52.0	73.9	95.8	118.6	142.3	165.9
	ppp	3.8	5.1	8.6	13.8	22.4	38.1	53.9	73.9	95.8	118.6	142.3	165.9
B1													
World	mex	20.9	26.8	36.2	52.1	73.1	100.7	135.6	171.6	208.5	249.8	290.0	328.4
	ppp	25.7	33.3	44.6	61.6	82.2	108.4	140.0	171.8	204.1	242.5	281.3	318.8
OECD90	mex	16.4	20.6	26.0	32.4	38.3	43.9	49.9	55.4	59.8	66.3	73.9	82.3
	ppp	14.1	17.7	22.4	28.1	33.3	38.3	43.6	48.5	52.5	58.4	65.1	72.7
REF	mex	1.1	0.8	1.1	1.7	2.8	4.3	6.2	8.2	10.3	12.8	15.3	18.1
	ppp	2.6	2.2	2.6	3.3	4.3	5.3	6.4	8.2	10.3	12.8	15.3	18.1
ASIA	mex	1.5	2.7	4.8	8.7	15.1	24.9	37.9	51.4	64.8	78.7	91.7	103.1
	ppp	5.3	8.2	12.0	17.3	24.6	34.1	46.1	57.4	67.7	79.3	91.7	103.1
ALM	mex	1.9	2.7	4.4	9.3	17.0	27.6	41.6	56.7	73.6	92.0	109.1	124.8
	ppp	3.8	5.1	7.6	12.8	20.1	30.6	44.0	57.8	73.6	92.0	109.1	124.8
B2													
World	mex	20.9	28.3	38.6	50.7	66.0	85.5	109.5	134.8	161.5	186.3	210.3	234.9
	ppp	25.7	34.8	46.9	60.2	75.5	93.2	113.9	136.8	160.7	183.8	207.4	231.8
OECD90	mex	16.4	21.1	26.5	30.3	33.1	35.8	38.3	40.9	44.4	47.9	52.0	56.6
	ppp	14.1	18.3	23.0	26.3	28.8	31.3	33.5	35.9	39.2	42.4	46.1	50.4
REF	mex	1.1	1.0	1.2	1.8	2.8	4.5	6.6	8.6	10.5	11.9	13.2	14.5
	ppp	2.6	2.4	2.7	3.3	4.3	5.6	7.2	9.5	11.6	13.3	14.8	16.2
ASIA	mex	1.5	3.5	7.2	13.2	21.3	30.7	41.8	52.7	64.1	75.0	85.8	97.1
	ppp	5.3	9.3	15.1	22.4	30.7	39.3	49.3	59.0	68.7	78.5	89.2	100.4
ALM	mex	1.9	2.7	3.7	5.5	8.8	14.6	22.8	32.6	42.6	51.4	59.3	66.8
	ppp	3.8	4.9	6.2	8.2	11.7	17.0	23.9	32.4	41.2	49.6	57.2	64.9

Resource Availability

Table 3.2 summarizes the resource availability assumptions for all the SRES scenario families and scenario groups within the A1 scenario family. Eight categories of conventional and unconventional oil and gas reserves, resources and additional occurrences are listed as are the assumptions of their availability as used in the SRES scenarios. For comparison also historical and future scenario consumption figures are shown.

Table 3.2 Oil and gas resource availability assumptions underlying the IPCC SRES scenarios. Eight different categories of conventional and unconventional reserves, resources and occurrences are shown as well as which resource category is assumed to be available in which scenario. For comparison also historic, cumulative resource extraction as well as future use levels as resulting from the SRES scenarios are shown. In ZJ (10^{21} J or 1,000 EJ).

	Conventional reserves and resources	**Unconventional**			**Unconventional and additional occurrences**			
		Enhanced recovery	**Recoverable**					**Historical Consumption**
Category	**I,II,III**	**IV**	**V**	**VI**	**VII**	**VIII**	**Total**	**1860-1998**
Oil	12.4	5.8	1.9	14.1	24.6	35.2	94	5.1
Gas	16.5	2.3	5.8	10.8	16.2	800	852	2.4

Scenario/	**Scenario assumptions**						**Consumption 1990-2100**	
Category	**I,II,III**	**IV**	**V**	**VI**	**VII**	**VIII**	**Oil**	**Gas**
SRES								
A1B	gas/oil	gas/oil	gas/oil	gas/oil	gas	---	25.5	31.8
A1T	gas/oil	gas/oil	gas/oil	gas/oil	gas	---	20.8	24.9
A1O&G	gas/oil	gas/oil	gas/oil	gas/oil	gas/oil	gas	34.4	49.1
A1C	gas/oil	gas/oil	gas/oil	---	---	---	18.5	20.5
A2	gas/oil	gas/oil	gas/oil	gas	---	---	19.6	24.5
B1	gas/oil	gas/oil	Gas	gas	---	---	17.2	23.9
B2	gas/oil	gas/oil	gas/oil	gas	---	---	19.4	26.9

The resource availability assumptions of the three base case scenarios analyzed here can be characterized as typical "middle of the ground". Thus, no scenario in the present study assumes either extremely large (e.g., in form of methane hydrates) or extremely low availability of oil and gas resources.

Technology

The tree base case scenarios adopted follow the technology assumptions as outlined for the IPCC SRES scenarios. The main characterization (next to efficiency and emissions) of technologies for the SRES scenarios concerns their costs over time. Costs are treated as dynamic and in addition, embrace an endogenous technological change perspective, i.e., improvements in costs are linked to (cumulative) deployment rates. In other words, an initially expensive technology can get only less expensive in cases it is deployed (learning by doing hypothesis). If it remains "on the shelf", there is no endogenous mechanism of cost improvement. A summary of selected advanced energy technologies and their levelized costs is given in Table 3.3.

It should be noted that not all technology and costs assumptions from the SRES report are pertinent to the scenarios analyzed here due to additional constraints such as a ban on nuclear energy (see next section). Furthermore, it is important to emphasize that the very nature of the two sustainable development base case scenarios (A1T and B1) implies a very dynamic (or in using a value statement extremely optimistic) outlook on the possibilities to improve efficiency, versatility, and above all the economics of advanced energy technologies. Only scenario B2 is more moderate in its technology assumptions, but it is important to retain that the analysis reported here does not include technology scenarios in which advanced energy technologies are not forthcoming or its costs are not improving at all.[7] Given this dynamic technology

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[7] This in fact continues to be a characteristic of many climate policy models, in particular those (top-down) models deploying the concept of a (static) back-stop technology.

outlook, the comparatively modest costs of climate stabilization reported in the next chapter should therefore not be surprising – even if the limits imposed by analyzing only three scenarios (in fact in technology terms only two, i.e., A1T/B1 versus B2) compresses the inevitable uncertainty innovation and long-term technology development entails.

Table 3.3 Range (min/max) of levelized costs for selected advanced energy technologies by 2020 and 2050 for the three scenarios analyzed in this report. In US cents(1990) per kWh (excluding fuel costs).

Costs of electricity generation technologies (UScent/kWh)				
	2020		2050	
A1-450	min	max	min	max
IGCC	3.2	3.2	2.8	2.8
NGCC	1.1	1.1	0.9	0.9
Biomass (including CC and single steam cycles)	2	3.1	1.9	2.4
Wind	3.5	3.5	1.7	1.7
Hydro (including large and small hydro)	0.9	8	0.9	8
Solar thermal	3.2	4.8	1.9	2.8
PV	3.7	5.4	1	1.5
Geothermal	2.7	2.9	2.5	2.9
Nuclear	2.6	3.7	2.5	4
	2020		2050	
B1-400	min	max	min	max
IGCC	3	3	2.8	2.8
NGCC	1	1.3	0.8	1
Biomass (including CC and single steam cycles)	2	3.1	1.9	2.6
Wind	3.9	3.9	2.6	2.6
Hydro (including large and small hydro)	0.9	8	0.9	8
Solar thermal	3.2	4.8	2	3.1
PV	4.2	6.1	1.6	2.4
Geothermal	2.7	2.9	2.5	2.9
Nuclear	2.6	4	2.6	4.5
	2020		2050	
B2-400	min	max	min	max
IGCC	3.2	3.3	3	3.1
NGCC	1.6	1.6	1.2	1.2
Biomass (including CC and single steam cycles)	2.1	3.4	2.1	3
Wind	4.5	4.5	3.4	3.4
Hydro (including large and small hydro)	0.9	8	0.9	8
Solar thermal	3.5	5.2	2.6	3.9
PV	4.9	7.1	2.7	4.2
Geothermal	2.9	2.9	2.9	2.9
Nuclear	2.6	4	2.6	3.8

3.3.3 Additional WBGU Constraints

Both, the A1T and B1 WBGU background scenarios as well as the respective stabilization scenarios differ to their IPCC SRES and TAR counterparts with respect to a number of additional constraints imposed on the deployment of zero-carbon options (nuclear, biomass, hydro power, and carbon sequestration). The constraints were specified by the WBGU in order to ensure sustainability of zero-carbon energy use, addressing also the risk of non-permanent CO_2 sequestration (see the forthcoming "WBGU Sondergutachten" for a more detailed discussion).

The following WBGU constraints are considered (quantifications are given for the world):

- The potential of biomass use (including non-commercial biomass) is limited to 100 EJ
- Hydropower is limited to 12 EJ in the medium term and 15 EJ in the long term
- All nuclear plants are phased out globally until the year 2050
- CO_2 capture and storage is assumed to be a tentative solution for the next hundred years (phase out 2100), and cumulative CO_2 capture and storage from 2000 to 2100 is constraint to 300 GtC.[8]

The WBGU constraints represent stringent limitations for zero-carbon energy, and have a considerable impact on the carbon mitigation potential of the stabilization scenarios. The aggregated effect of the constraints was too restrictive in the case of A1T-450 scenario and led to model infeasibilities. In order to achieve a robust model solution under the given constraints, it was, hence, necessary to introduce additional changes to the A1T assumptions as compared to the original A1T SRES scenario. In this respect, the penetration of renewable hydrogen production technologies and the diffusion hydrogen fuel cell vehicles in the transportation sector are assumed to take place at a much higher pace than in A1T-SRES. In addition, the WBGU scenario assumes also higher shares of electricity-based transportation for the medium term (enabling the decarbonization of the transportation sector via renewable electricity and/or fossil power with carbon capture and sequestration). Most importantly however, the WBGU A1T scenario assumes also considerably higher improvements of energy intensities of GDP, and does not include the WBGU constraint with respect to carbon capture.

None of the above-mentioned WBGU constraints was considered during the development of the WBGU B2 scenarios, particularly because the SRES B2 baseline scenario describes a comparatively pessimistic development, assuming the continuation of historical trends along a "dynamics-as-usual" and non-sustainable path. It is, hence, unlikely that the stringent stabilization target (400 ppmv) can be achieved under the restrictions for the energy portfolio as suggested by the WBGU constraints.

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[8] One of the main differences to the comparable scenarios reported in the IPCC TAR is that the present WBGU scenarios in addition also consider carbon sequestration from biomass derived electricity and hydrogen production facilities.

4 Policy Scenarios

4.1 CO_2 Stabilization Levels

GHG concentrations stabilization levels in the WGBU scenarios correspond to the stabilization of atmospheric CO_2 concentrations at 400 and 450 ppmv. This climate stabilization target is based on limiting future climate change to below global mean temperature change of 2 degrees C and assuming an intermediary climate sensitivity. This climate change target yields a CO_2 concentrations stabilization level of some 400 ppmv.[9]

For the high demand scenario SRES-A1T this climate stabilization target is not feasible for the range of original input assumptions and additional constraints and model parameters adopted within the framework of this study. Hence, a somewhat higher stabilization target of 450 ppmv (consistent with the scenarios reported in IPCC TAR albeit a half-a-century earlier achievement of the stabilization earlier in the WBGU scenarios) was adopted.

It is important to recall that while similar climate stabilization targets have been frequently advanced in the literature, there remains considerable scientific uncertainty with respect to what constitutes any particular threshold value of “acceptable” or “not dangerous” climate change. This is due to both the non-linear responses of the climate system (e.g., abrupt temperature change versus gradual, smooth changes) to any given change in atmospheric concentrations of GHGs that remain to be poorly understood, as well as to the considerable uncertainties surrounding estimates of vulnerability and resilience of natural (managed and unmanaged) ecosystems and societies (human activities) *vis à vis* any given level of climate change. Hence the scenarios reported here should be considered as illustrative – even though very stringent – precautionary response strategies to future climate change. The model calculations reported here should therefore not be interpreted as endorsement or preference of these particular stabilization levels over alternative ones, including less stringent scenarios; nor, conversely as an interpretation that these 400 to 450 ppmv stabilization scenarios constitute indeed a level of “non-dangerous” interference with the climate system.

The uncertainties are too large to be able to derive such conclusions. For example, most of the 40 SRES emissions scenarios can lead to a 2 degrees Celsius average global mean temperature change by 2100 assuming a choice of “appropriate” climate sensitivity. In other words, climate sensitivity accounts for as much uncertainty of future climate change range as do future emissions as described by the full range of SRES scenarios (IPCC, TAR Synthesis Report, 2002). The range of stabilization scenarios reported here should therefore simply be interpreted as illustrative model calculations for particular climate stabilization target levels chosen as exogenous study assumptions, reflecting the research interests for this study, rather than a scientific endorsement of the particular stabilization levels analyzed.

Given the exogenously defined stabilization levels of atmospheric CO_2 concentrations, both the MESSAGE and the MAGICC model were used iteratively to derive global, cost minimal CO_2 emission trajectories consistent with the climate stabilization targets (see Figure 4.1). In turn, this forms the input for the subsequent

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[9] The calculations for the stabilization scenarios were done with the MAGICC model and a calculation horizon up to the year 2300. The resulting climate sensitivities consistent with the goal of remaining below 2 degrees realized global warming and for the stabilization levels analyzed here ranges between 2 to 2.9 degrees C per doubled CO_2 concentration.

step of emission entitlements allocation that constitutes the basis for the model calculations of international trade in carbon emission entitlements and for actually realized emission reductions under a marginal abatement cost minimization criterion.

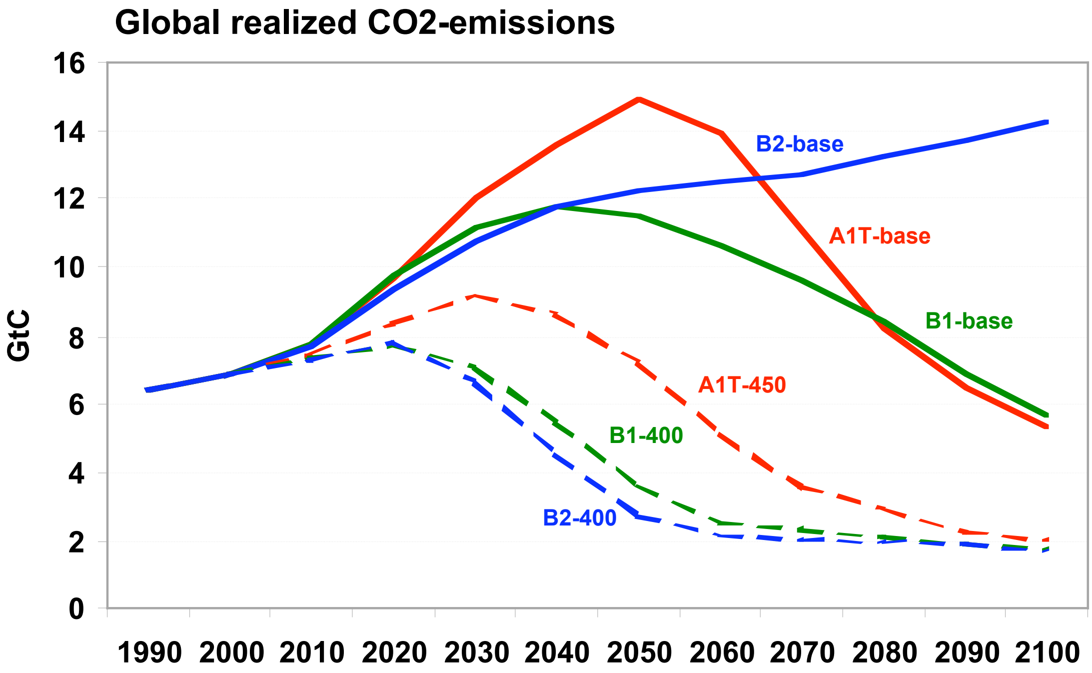

Figure 4.1: Global CO_2 emissions of three alternative baseline scenarios: WBGU-A1T, WBGU-B1, and WBGU-B2[10] *and corresponding emission profiles consistent with stabilization at 400 ppmv (B1-400, B2-400) and 450 ppmv (A1T-450) respectively. In GtC.*

4.2 Allocation Criteria

The three stabilization scenarios are based on a separation of the economic issues of equity and efficiency (which consistent with the prevailing economic theory and most of stabilization scenarios in the literature). Thus, the issue of allocation emission rights is separated from the issue of economic efficiency in achieving pre-scribed emissions reduction profiles, leading to atmospheric CO_2 stabilization. In other words, the scenarios assume international agreement on ultimate climate stabilization goals (in this case on 400 and 450 ppm CO_2 by 2100 and hence on cumulative carbon emissions) as well as on the allocation of resulting GHG emission entitlements. Grübler and Nakicenovic (1994) have proposed a number of alternative allocation mechanisms within the context of international burden sharing in GHG emission reductions. They proposed a two-tired classification of alternative burden sharing schemes based on *reductive* versus *distributive* criteria.

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[10] These three baseline scenarios differ from those presented in the IPCC SRES in terms of continued model improvement such as a different calibration of the year 2000 values for which (contrary to SRES and TAR) actual energy and GHG emissions statistics are now available as well a full reflection of the current outlook on the implementation of the UNFCCC Kyoto Protocol in case of the climate stabilization scenarios, and most importantly also with respect to the implementation of the WBGU constraints.

Reductive criteria follow the traditional command-and-control environmental policy approach, in terms that a given environmental (emission reduction) target is first defined and then the required emission reduction is distributed according to various schemes. Two of these reductive criteria have figured prominently in the literature (for a detailed overview see Grübler and Nakicenovic, 1994; and IPCC SAR, 1996:83-124): equal percentage emission cuts (also referred to as emission "grandfathering" due to its insensitivity to differences in initial conditions and initial preservation of emission status quo, particularly for large emittors), and cutbacks proportional to historical contribution (a responsibility based approach of burden sharing underlying for instance the Brazilian proposal for a sequel to the Kyoto protocol).

Conversely, *distributive criteria* take a different point of departure. They consider the assimilative capacity of the atmosphere as a global commons resource to be distributed according to different equity principles. A prominent example for this type of criterion are equal per capita emission entitlements. Due to the enormous asymmetries between population and GHG emissions between UNFCCC Annex-I and non-Annex-I countries, such a *distributive* criterion necessarily implies the existence of a functioning global market for trade in emission permits, as an immediate implementation of such an allocation scheme as emission *reduction* rule would require such drastic emission reductions in Annex-I countries to be infeasible technically, economically, as well as politically. However, such simplistic criteria ignore important aspects of intergenerational equity, as ignoring the "common but differentiated" responsibility (UNFCCC, 1992) for creating the environmental externality in the first place. An interesting model has been developed by Fujii (1990), who postulates that access to the global commons such as how much carbon can ultimately be released into the atmosphere should be distributed equally among all people inhabiting the planet, irrespective of place and time they live. In other words per capita emissions need to be equalized not only across countries but also across subsequent generations.[11]

It goes without saying that the debate about alternative burden sharing schemes and various equity concepts these are based on continues with no scientific consensus in sight. As a result, most studies explore a range of alternative burden sharing (emission entitlements allocation) models that are then tested for their implications on carbon trade and financial transfer flows. Given the methodologies available for this type of analysis, it is not surprising that nearly the entirety of the literature follows the principle of economics of sharply separating equity from efficiency. In other words, whereas many alternative emission entitlement models are possible (and indeed explored in the literature), the actual emission reduction calculations invariable embrace a marginal cost equalization (minimization) approach. In other words, regional with higher emissions than their allocation have the economic choice of either reducing emissions domestically or to buy emission "credits" from regions that have either lower emissions than their entitlements (often referred to by skeptics as trade in "hot air"), or to invest in emission reductions in regions that have lower emission reduction costs, accruing corresponding emission credits. Due to enormous differences in initial conditions, projected growth in future emissions, technology availability, etc. a vigorous formal modeling framework is required to perform actual

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[11] For the low stabilization scenarios analyzed here, the Fuji model when calculated over the period 1800-2100 would imply that emission entitlements for Western Europe would immediately drop to some 0.5 tC per capita and for North America even would become immediately negative (to compensate for over-proportional high historical per capita emissions), implying vast trade (and resource transfers) flows from Annex-I to non-Annex-I countries.

calculations of levels of emission reductions and trade in carbon emission credits. The IIASA integrated assessment methodology has the added advantage of also taking macro-economic feedback effects from resulting energy price increases and revenues/losses from carbon trade formally into account.

In this study two variants of a "hybrid" burden sharing allocation mechanism are explored following a proposal from the study sponsor (WBGU). This burden sharing scheme is referred to as a "contraction and convergence" scheme in the literature (see e.g., den Elzen, 2002). In essence, all regions need to converge to a common per capita emission entitlement by a given pre-specified date (2050, and 2100 respectively in this study, hence the scenario designation as c&c2050 and c&C2100 respectively).

For regions with above world average per capita emissions this implies immediate linear reductions (hence the term "contraction") until the convergence criterion is fulfilled, however starting from very different initial conditions. (Thus this criterion also contains certain elements of emissions "grandfathering", this being the reason it is referred to here as "hybrid" approach). For (developing) regions below world average per capita emissions, emissions can rise initially until the world average per capita emission level is reached. Thereafter, also developing regions need to "contract" to the pre-specified convergence level.[12] Depending on the demographic scenario underlying the base case scenario (low in the A1T and B1 scenarios, medium in the B2 scenario), as well as on the required stabilization level (450 ppmv for A1T and 400 ppmv for the other two scenarios), per capita emissions converge to different, but overall very low levels. For instance in the c&c2050 scenarios, global per capita carbon emissions converge to levels between 0.3 (B1-400) to 0.8 (A1T-450) tC/capita, in order to decline further thereafter to as low as 0.2 tC/capita by 2100.

The differentiation between 2050 and 2100 as alternative years for per capita emission entitlements convergence results however in comparatively little difference. Postponing the convergence year to 2100 eases the transition for the Annex-I countries somewhat at the expense of the developing countries, but differences in cumulative emissions are comparatively small: 24-37 GtC difference for the Annex-I countries between the two c&c schemes across the three base case scenarios analyzed, to be compared with cumulative (1800-2100) emissions of between 370 and 413 GtC for Annex-I countries in the c&c2050 scenarios. Figure 4.2 presents the results of the carbon emission entitlement allocation for the three scenarios and the two c&c emission allocation schemes.

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[12] Formally, the algorithm used is $S_{y+1} = S_y - (S_y - P_{y+1})\ (t / t_{conv})$ where Sy is the emissions share of a region in the year y, Py is its share of the global population (subject to the emission cap) in year y, t is the time elapsed between 2010 and the target year, and t_{conv} is the total time until convergence has to be achieved (if convergence target is 2050, t_{conv} is 40 years). See also http://www.gci.org.uk/contconv/cc.html on this type of allocation scheme and calculus.

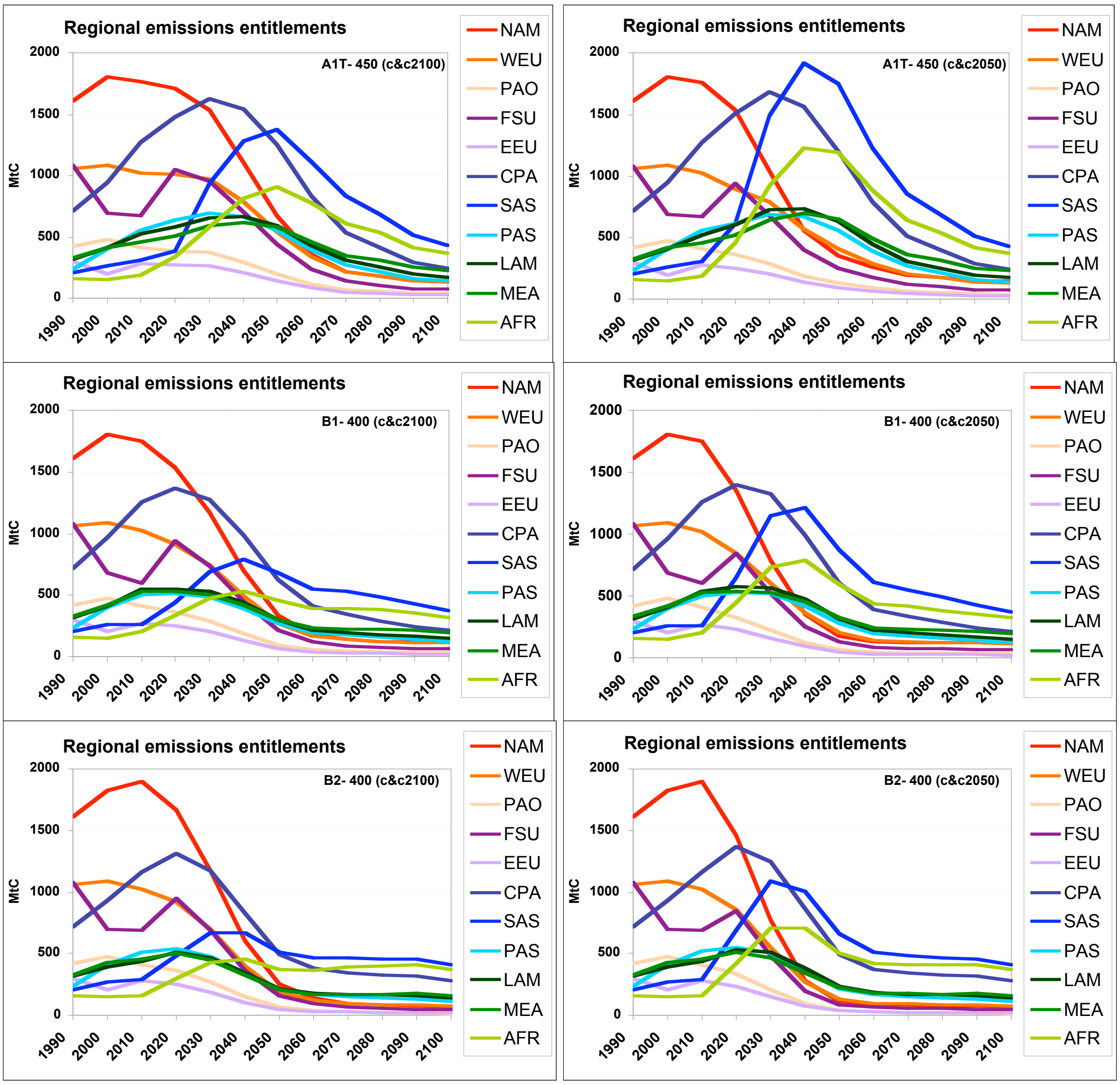


Figure 4.2: Regional emission entitlements for three climate stabilization scenarios (A1T-450, B1-400, B2-400) under two allocation schemes (c&C2050, and c&c2100). In MtC.

Given the state of the scientific and policy debate, there is no single widely accepted burden sharing scheme, and it is also highly unlikely that the "contraction and convergence" (c&c) scheme analyzed here for WBGU has the potential to gain the necessary wide "buy in" required for an international agreement on such an intricate issue. Each scheme proposed has its individual strengths and weaknesses. The c&c scheme here quite legitimately attracts criticisms from Annex-I countries of not sufficiently considering differences in initial starting conditions and for providing an incentive for unfettered population growth in the "South". Conversely, developing countries quite legitimately object such schemes because they ignore the "differentiated" responsibility in creating the climate change externality in the first place. For instance, Annex-I countries have caused about half of all CO_2 emissions (and about two thirds of energy-related emissions) since the onset of the Industrial Revolution while accounting for only some 20 percent of global population, a disparity that largely remains preserved under the two WBGU emission allocation schemes analyzed here (see Table 4.1).

Table 4.1 Share of different regions in cumulative population and cumulative carbon emissions over the period 1800 to 2100 for the scenarios analyzed in this study. In percent.

5	**Cumulative population**		
	A1T	B1	B2
OECD	15	15	13
REF	7	7	6
ASIA	49	49	51
ALM	28	28	30
Cumulative emissions in Baseline			
	A1T	B1	B2
OECD	33	37	36
REF	13	14	13
ASIA	32	28	30
ALM	22	22	21
Cumulative emission entitlements (c&c2050)			
	A1T-450	B1-400	B2-400
OECD	36	40	40
REF	12	13	13
ASIA	31	28	28
ALM	21	20	19
Cumulative emission entitlements (c&c2100)			
	A1T-450	B1-400	B2-400
OECD	39	42	43
REF	13	14	14
ASIA	29	26	26
ALM	19	18	17

For instance, the stabilization scenarios lead to the almost paradoxical situation that the share of Annex-I countries in cumulative emissions (and hence in contribution to radiative forcing change) increases compared to the unabated baseline scenarios. It appears thus that the critical participation of developing countries in climate mitigation efforts cannot be considered as probable, unless some alternative formula is found that also incorporates considerations of historical responsibility and that assures that global emissions inequities do at least not increase in a climate control regime.

The fact, that only one particular burden sharing scheme is explored in more detail in this study, has therefore to be considered as important shortcoming, calling for further in-depth analysis of alternative proposals and should not be interpreted as endorsement of this particular type of burden sharing scheme over other, alternative reductive or distributive criteria (or combinations thereof).

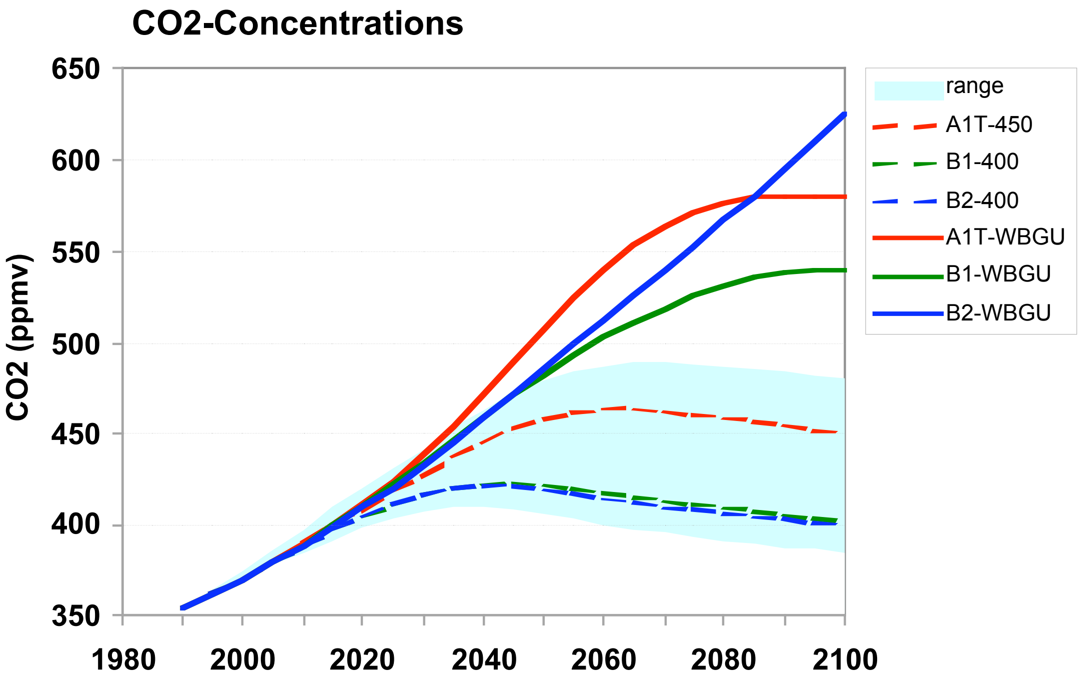
4.3 Results

4.3.1 Emissions, Concentrations and Climate Change Implications

Before discussing the structure, measures, and economic implications of the climate stabilization scenarios in more detail below we summarize first the climate implications of the scenarios analyzed.

Figure 4.1 above showed the global carbon emissions in the six main scenarios analyzed (three base case and three additional climate stabilization scenarios). Cumulative historical and future carbon emissions (as a first rough proxy variable for changes in radiative forcing) range between 1200 (B1) and 1400 (B2) GtC over the period 1800 to 2100, compared to a range between 700 (B2-400) and 900 (A1T-450) GtC in the stabilization scenarios. In this context however, one needs to keep in mind that two of the three scenarios (with exception of scenario B2) embrace a sustainable development paradigm, leading even in absence of climate policies to comparatively low emissions, as well as the invariably low stabilization levels (400 and 450 ppmv) analyzed in this study. The limitation of assumed mitigation options and measures also leads to an "upper limit" on the cumulative emissions "avoided" across the three stabilization scenarios.

The "simple" climate model, MAGICC, has been integrated into the IIASA assessment framework. It was used to assess climate change implications of the GHG and aerosol emissions of the three WGBU scenarios. Figure 4.3 shows the resulting changes in atmospheric CO_2 concentrations, global mean temperature change, as well as sea level rise (Figures 4.3a, 4.3b, and 4.3c).



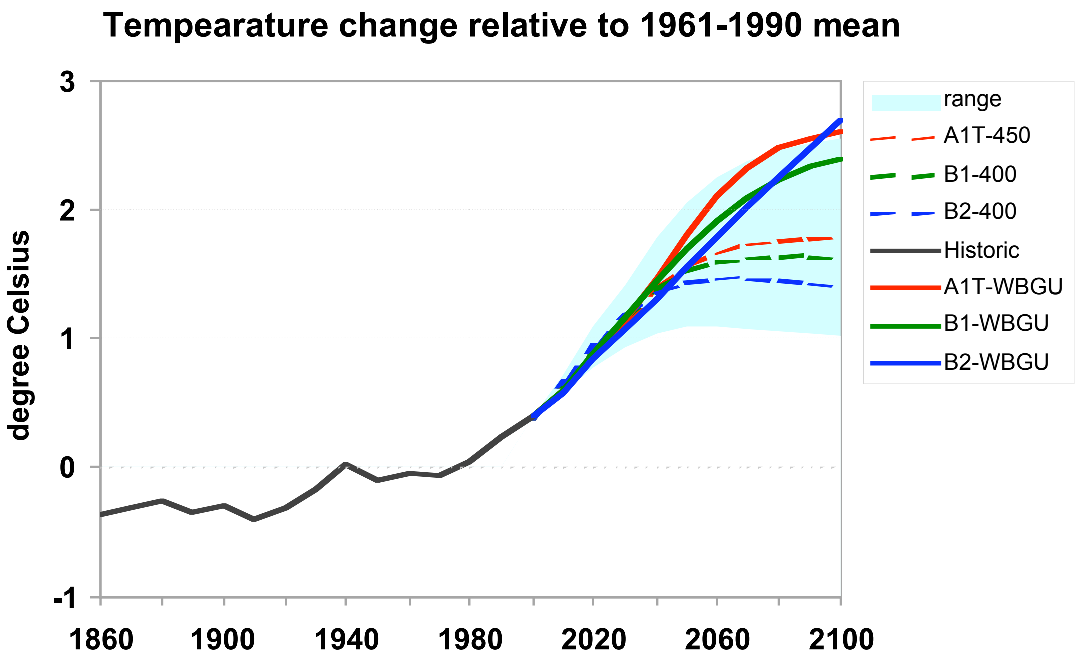


Figure 4.3b: Global mean temperature change, compared to the 1961 to 1990 mean for the six scenarios analyzed. The shaded area indicates the model uncertainty for the three stabilization scenarios. In degrees Celsius.

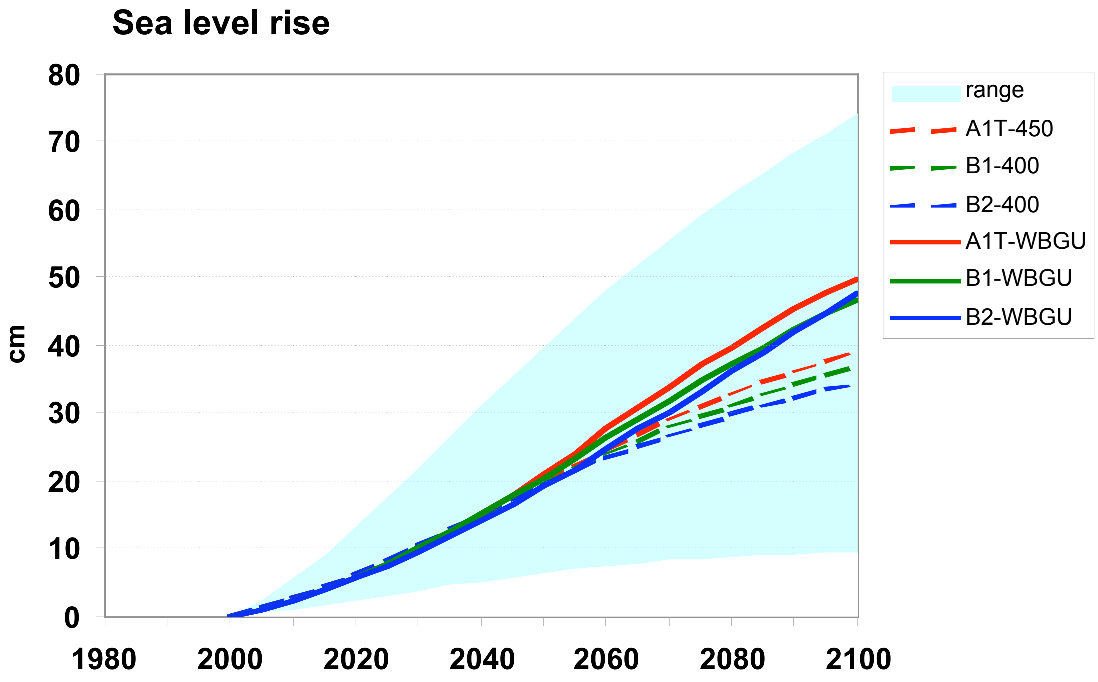


Figure 4.3c: Sea level rise resulting from global warming (Figure 4.3b) for the six scenarios analyzed. The shaded area indicates the model uncertainty for the three stabilization scenarios. Note in particular the continuous rising trends of sea level rise beyond the study horizon (2100) and the substantial uncertainties. In cm sea level rise compared to 2000.

The three figures confirm a phenomenon frequently discussed in the literature, i.e., the effect of compounding uncertainties. With each successive step in the analysis, i.e., translating carbon emissions to atmospheric CO_2 concentrations, these in turn to global mean temperature change, and the latter into sea level rise, uncertainties increase substantially.

Whereas atmospheric concentration uncertainties in the three climate stabilization scenarios are substantial, they nonetheless invariably remain below the best guess estimates of their corresponding no-policy scenarios. Conversely, uncertainties in projected global mean temperature change are much larger: embracing even the best guess projections of the no-policy base scenarios. In other words, based on current scientific understanding of climate sensitivity uncertainties, it is impossible to deduce that the climate stabilization scenarios analyzed here would indeed lead to lower levels of global warming than their unabated scenario counterparts, if the latter would unfold under a low range of climate sensitivity, but the stabilization scenarios would have to face a situation of high climate sensitivity. Nonetheless, even given inevitable uncertainties, the model calculations confirm that lower emissions indeed lead *ceteris paribus* (which in this case is an important qualifier) to lower levels of realized global mean temperature change and thus to reduced risks of adverse climate change impacts.

Finally, it is instructive to consider the uncertainties in projected sea level rise (Figure 4.3c). By 2100, the best guess estimates of sea level rise reduce the risk from some 50 cm increase in the no-policy scenarios to below 40 cm in the policy scenarios. Considering the enormous inertia embedded in the climate system and its impacts on the oceans this difference between the scenarios should be less surprising, as is the enormous uncertainty range (less than 10 cm to well above 70 cm by 2100 in the climate stabilization scenarios). More importantly, constraining the analysis to the study horizon of 2100 (as done in Figure 4.3c) would give a wrong sense of complacency, as due to inertia sea levels would continue to rise even under strict climate stabilization scenarios for hundreds of years into the future. The best guess model calculations indicate that by 2300 sea levels could continue to rise in the stabilization scenarios to levels between 62 to 75 cm above today's levels, with an uncertainty spanning an extremely wide range: 8 cm to 164 cm (i.e., from a non-problem to an extremely serious issue for low lying islands and coastal areas). Thus, the example illustrates well the deep uncertainties and the importance of inertia and time lags in climate change responses inherently involved in the climate change debate. In addition, the uncertainties, particularly on the climate change impact side compound to such a wide range as leaving all the room for policy interpretations, spanning the extremes of “do nothing” complacency to an alarmist call for “hitting the brake as fast as possible” policy intervention.

4.3.2 Emissions, Reductions, and Carbon Trade

As mentioned above, the starting point for the analysis of climate stabilization scenarios are three unabated scenarios, modified after their corresponding “parent” (baseline) scenarios from the IPCC SRES report (SRES-A1T, SRES-B1, and SRES-B2). The climate stabilization scenarios constrain global carbon emissions as to lead to the pre-scribed stabilization levels of 450 and 400 ppmv respectively (A1T-450, B1-400, B2-400). In turn these global allowable emissions levels are allocated over time based on two variants to the “contraction&convergence” algorithm described above. Subsequently the MESSAGE model is used to calculate actual regional and intertemporal emission reduction measures consistent with the global constraint but assuming full flexibility to actually perform emission reduction measures where and when[13] they are cheapest (cost minimization criterion). Figure 4.4 summarizes the resulting emissions cumulated over the entire time period 2000 to 2100 for the nine scenarios analyzed and compares these cumulative emissions with historic emissions over the period 1800 to 2000. In order to illustrate the effect of flexibility, the figure shows both emission allocations as well as realized emissions, with the difference reflecting international carbon trade.

Given the nature of the c&c emission entitlements schemes, a general pattern is that of imports of emission credits into the OECD regions from the developing regions (ASIA and ALM). This is graphically visible in the Figure 4.4 where realized emissions in the OECD region systematically surpass those allocated as emission entitlements. A further robust finding from the analysis, is that by postponing the convergence date of per capita emission entitlements from 2050 to 2100, larger emission entitlements are allocated to the OECD countries, reducing thus the need for carbon trading.

Contrasting the difference between emission entitlements and realized emissions, with that of the baseline scenarios indicates the relative importance of “domestic” emission reduction, versus carbon trade. Given the long-term and stringent emission reduction goal underlying the scenarios analyzed, it is not surprising to see that cumulatively trade remains a comparatively small measure compared to “domestic” emissions reduction, indicating in addition that the frequently discussed problem of carbon “leakage” due to tradable emission permits should remain comparatively low under the scenarios analyzed, furthering their political viability.

However, the cumulative aggregates in Figure 4.4 mask important inter-temporal variability in carbon trade over time. As a rule, carbon emission credits imports into the OECD peak in the period 2020 to 2050, especially around 2050 when the additional WBGU constraints, such as a phase out of nuclear power, render the compliance to the climate stabilization goals very difficult. This is also the period of a temporary price “hike” in the carbon permits traded (cf. discussion below). However, also trade *within* developing countries is important in the scenarios (masked in the regional aggregates of Figure 4.4).

For instance, in the second half of the 21st century, China and the Middle East would emerge as major importers of carbon permits from the Indian and African continents with revenue flows of equal order of magnitude than for the some OECD regions (e.g., North America). These detailed regional carbon trade and revenue flows are however not robust as arising from the specific assumptions and constraints characterizing the scenarios analyzed here. For a more comprehensive picture additional scenarios would have to be examined and resulting trade and revenue patterns aggregated to arrive at more robust conclusions with respect to financial “winners” and “losers” from carbon trade under stringent climate stabilization scenarios. Figures 4.5 and 4.6 give more detail on the international trade in carbon and the resulting resource transfers (revenue/investment flows from OECD to developing countries).

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[13] A discount rate of 5 percent is used in all model calculations reported here.

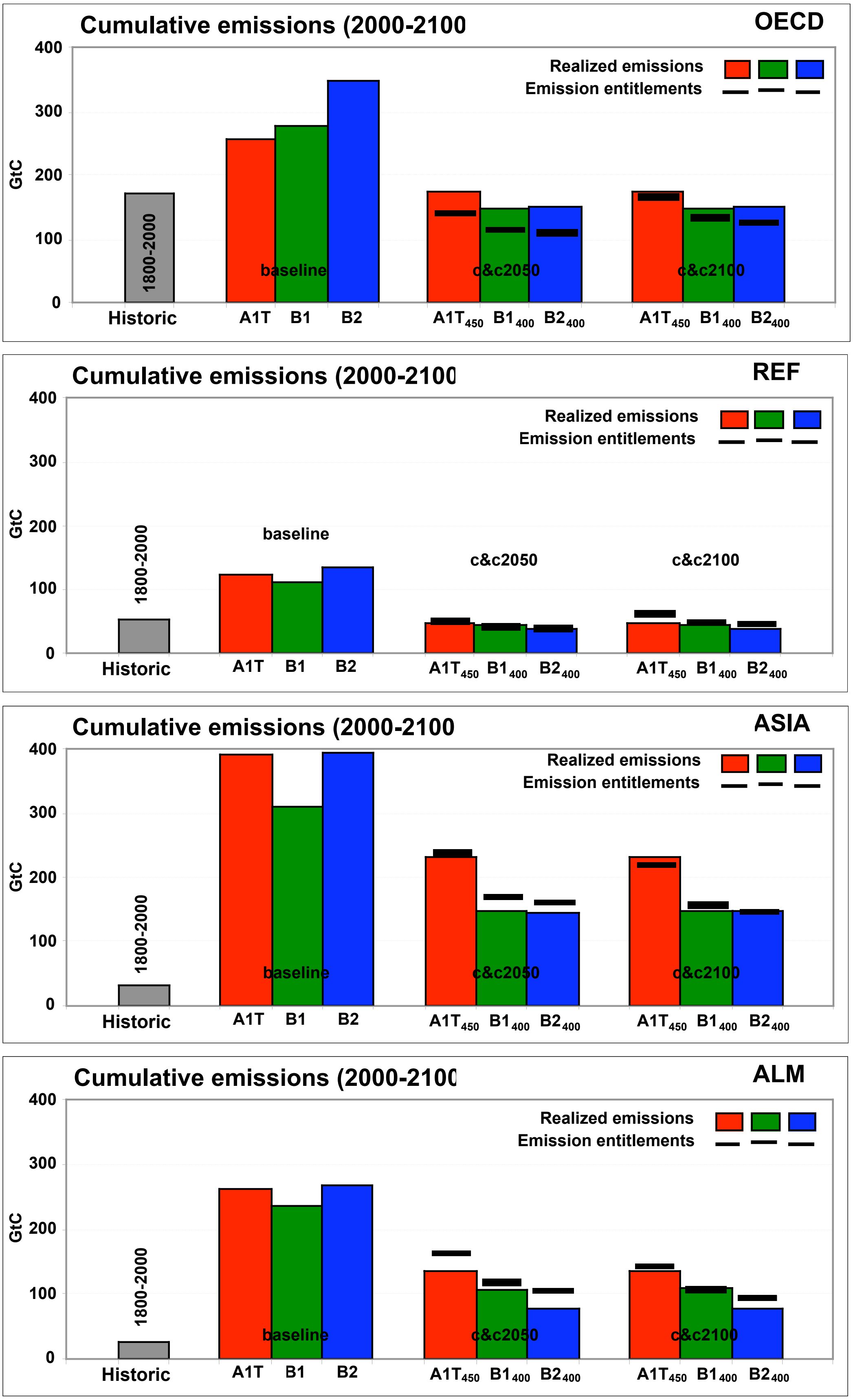
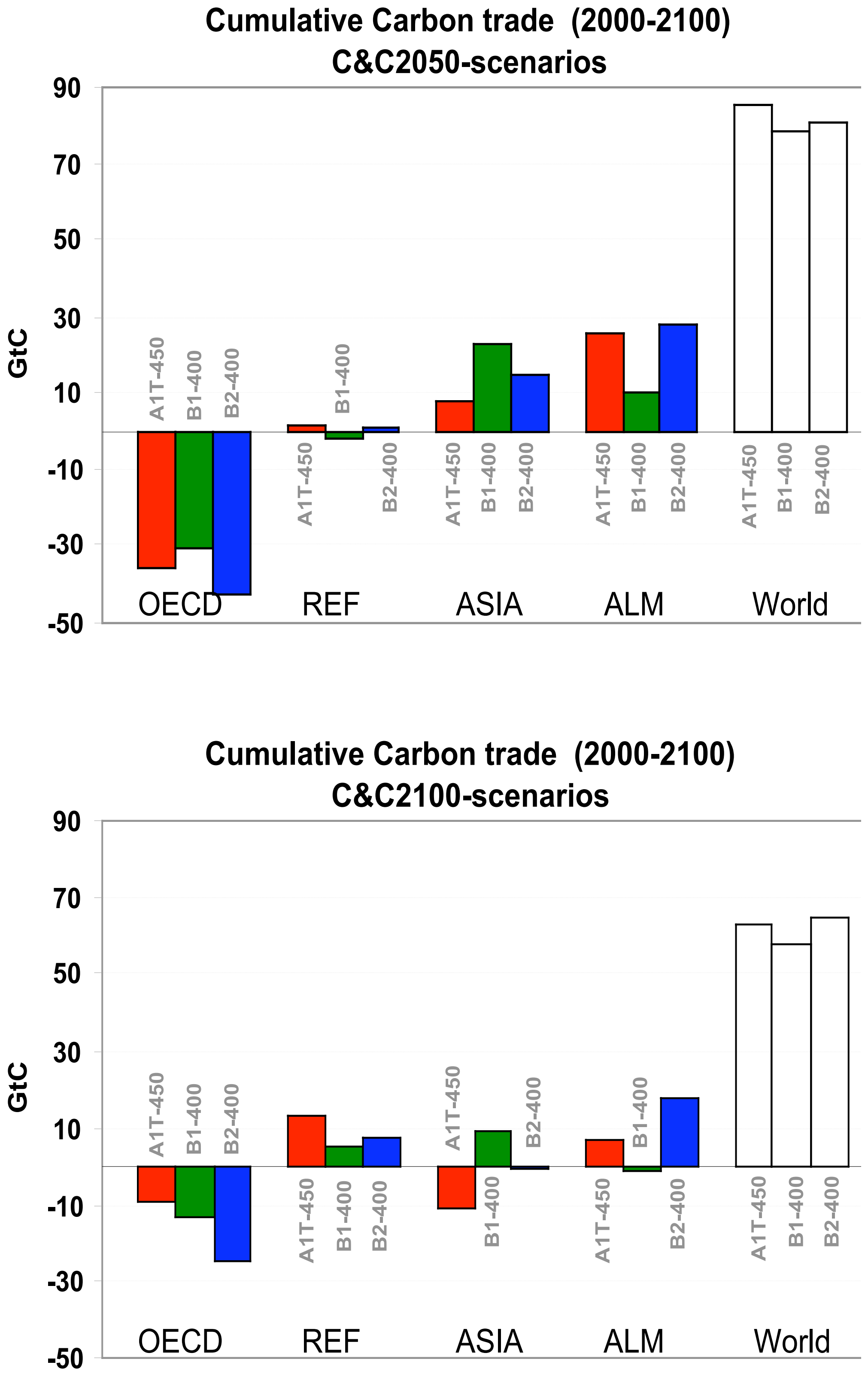


Figure 4.4: Cumulative energy and industry carbon dioxide emissions, historic (1800 to 2000) and future (2000 to 2100) for the three baseline scenarios and the six climate policy scenarios analyzed for four macro-regions. In GtC.



Cumulative Carbon trade (2000-2100)
C&C2050-scenarios

Cumulative Carbon trade (2000-2100)
C&C2100-scenarios

Figure 4.5: Cumulative (2000 to 2100) carbon trade flows for the six climate stabilization scenarios and for the four macro-regions assuming convergence of per capita emission entitlements by 2050 (top panel) or by 2100 (bottom panel). In GtC.

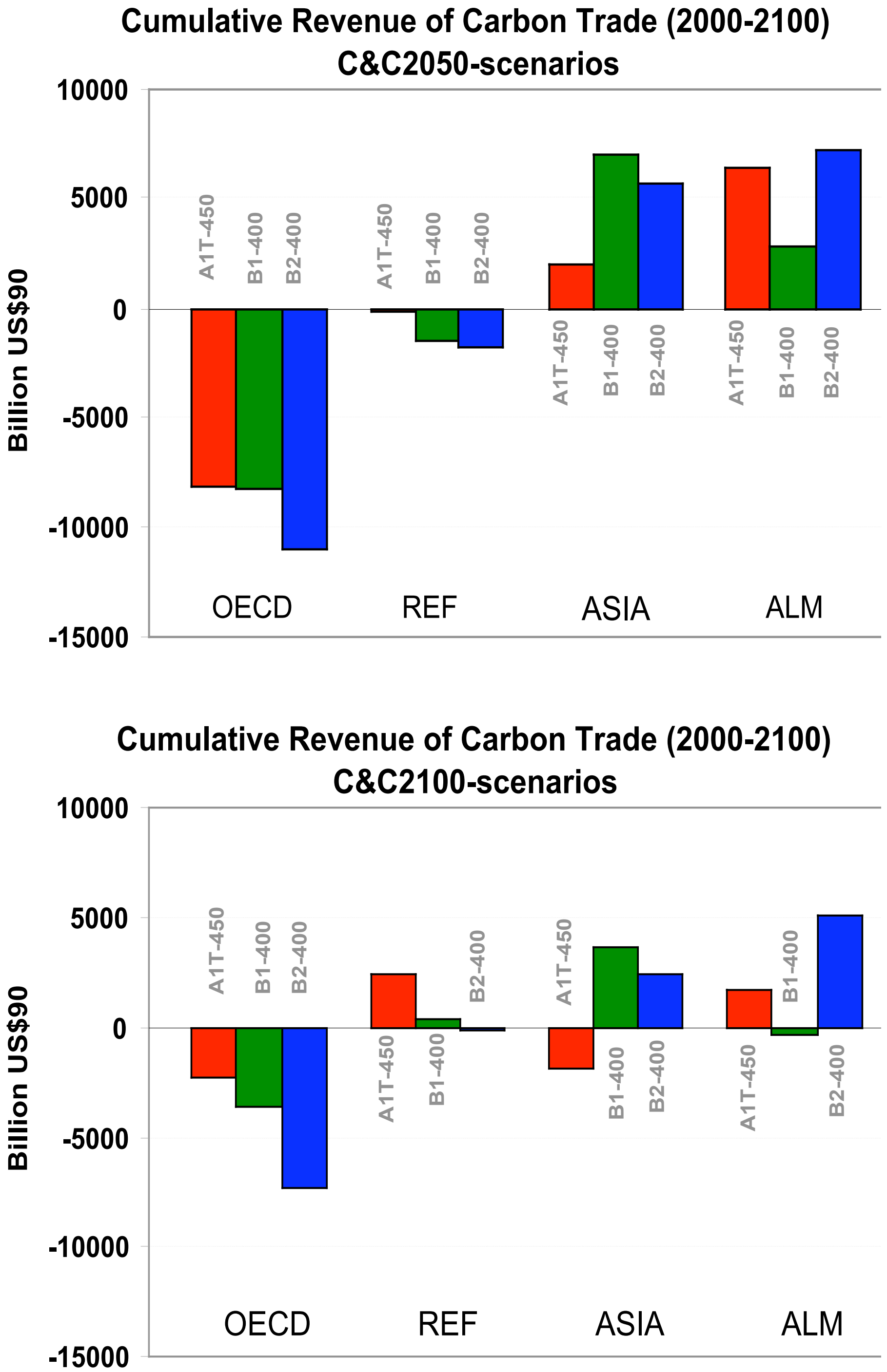


Figure 4.6: Cumulative (2000 to 2100) revenues from carbon trade for the six climate stabilization scenarios and for the four macro-regions assuming convergence of per capita emission entitlements by 2050 (top panel) or by 2100 (bottom panel). In Billion US$(1990).

The revenue flows from carbon trade (Figure 4.6) mirror the picture already shown above (Figure 4.5) for the physical volumes of carbon trade, except of course that when the comparison is made on a intertemporal basis, revenues increase generally faster than physically traded volumes due to the increasing carbon permit prices.

It constitutes an interesting finding of this study that the "contraction&convergence" algorithm of emission permit allocation – that in the literature is invariably assumed to favor net resource transfers to developing countries is in fact not unambiguous. Only in the case of an early convergence date of 2050 resource transfers remain systematically in direction from the OECD region to the developing and the reforming economies countries – easing thus their respective economic burden of emission reductions amidst economic development catchup. Conversely, if the convergence date is pushed out to 2100, the OECD region remains its position of "net payer", however the situation for developing countries and for the economies in transition deteriorates significantly. In fact, these regions – in their aggregate—become "net payers" in two of the three scenarios analyzed here. This variation is not scenario specific, but in its aggregate the results suggests that the variant of a contraction and convergence in per capita emission entitlements as late as 2100 is unlikely to find the wider acceptance from both transition economy as well as developing countries, required for the political sustainability of the proposed emission permit allocation regime.

Another significant finding from this analysis refers to the transition economies. Even as trade patterns in carbon emission permits are diverse across the scenarios examined, financial flows are in a persistent direction: the reforming economies would under the proposed emission allocation scheme c&c2050 examined become in aggregate (i.e., cumulatively over the period 2000 to 2100) net payers, even in scenarios where cumulative trade in emission permits is positive cumulated over the entire time horizon.

The reason for these seemingly paradox model results lie in the vast natural gas resources of the Former Soviet Union. After initially being able to sell vast amounts of "hot air", the transition away from reliance on natural gas towards the second half of the 21st century proves to be invariably extremely difficult across all scenarios, requiring the purchase of emission credits. Even as total trade flows remain positive (i.e., reforming economies remain net exporters of carbon credits cumulatively over the study horizon), the rising carbon price results in net resource transfers away from reforming economies. In other words: Russia sells low (before 2050) but buys high (after 2050).

Thus all scenarios indicate net resource transfers from both OECD and for most scenarios also from the reforming economies[14] away in direction of developing countries. The absolute magnitude of these resource transfers at first sight seems to be staggering: Over the period 2000 to 2100, Annex-I countries would transfer between US$8 to 13 trillion in direction of developing countries to buy emission credits (or to pay for mitigation measures) in developing countries, with the latter being the beneficiaries of these resource transfers (to be balanced however against the much higher mitigation costs arising from the stringent climate stabilization scenarios examined here). Considering however, that such resource transfer numbers are cumulative estimates over a 100 year period, annual averages are much less daunting: transfers from Annex-I countries would average between US$84 to 128 billion annually, with however substantial intertemporal variation. Nonetheless such numbers – even if small in comparison to the respective GDPs –- do not present financial "peanuts". After all, official development assistance (ODA) globally in the year 2000

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[14] Perhaps this model result helps to explain the reluctance of Russia to ratify the Kyoto Protocol. An important research task remains to investigate under which emission permit allocation regime and under which base case scenarios this unfavorable result for the transition economies could be eased; which would be an obvious pre-condition for acceptance of a stringent international climate control regime by the countries of this region.

amounted to some US$53 billion (UN, 2003[15]), significantly below the numbers for carbon permit trade suggested above.

4.3.3 Carbon shadow prices and macroeconomic implications

It is one of the outstanding features of the methodology developed at IIASA to resolve the much discussed dichotomy between “bottom-up” and “top-down” models in climate policy analysis. This is achieved by an iterative linkage procedure between the engineering type energy supply model MESSAGE that calculates energy systems costs, including marginal carbon abatement costs (shadow prices), and the macroeconomic model MACRO that balances changes in prices with resulting changes in energy demand as well as the impacts of rising energy and carbon prices on GDP. It is through this iterative approach that it became finally possible to resolve the discrepancies between the “bottom-up” and “top-down” perspectives, an important methodological issue that has haunted the climate change policy literature for more than a decade.

In essence, the discrepancy between “bottom-up” and “top-down” models arises from the myopia (or ignorance) of each class of models for representation of technology detail and the dynamics of technological change (a traditional strength of “bottom-up” models) on one hand, and for the consistent equilibration of prices versus quantities (a traditional strength of “top-down” models) on the other. The modeling framework developed at IIASA continues to be the only integrated assessment model available worldwide to have resolved this modeling dichotomy. This is particularly important for the present study as in terms of climate mitigation traditional “bottom-up” (B-U) and “top-down” (T-D) models continue to exhibit persistent biases ranging from the optimistic (B-U) to the pessimistic (T-D) as concerns feasibility and costs of climate mitigation measures. From this perspective, the modeling results presented here can claim significantly higher credence than that arrived with traditional modeling frameworks, subject of course to the limitations imposed by the type of scenarios analyzed as well as the assumption on intertemporal cost minimization that are shared invariably by *all* climate change policy analysis model available.

Figure 4.7 shows the calculated carbon permit price, or the globally equalized marginal carbon abatement costs for the six policy scenarios analyzed. A first important observation concerning Figure 4.7 is that differences in base case scenarios are more important than differences in the two emission permit allocation regimes studied. For all practical purposes of policy analysis, the economic cost differences between the two emission permit allocation schemes are negligible (even as was discussed above, resulting in trade patterns that are quite different between the two allocation models). This modeling result confirms our earlier observation that the costs of meeting a particular climate stabilization target is more dependent on the type of base scenario analyzed (high- versus low-emission futures) and the range of mitigation technologies available (unconstrained versus – as in this study – constrained) than on the absolute level of emission reduction or the particular model of emission permit allocation chosen.

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[15] See http://www.un.org/reports/financing/profile.htm

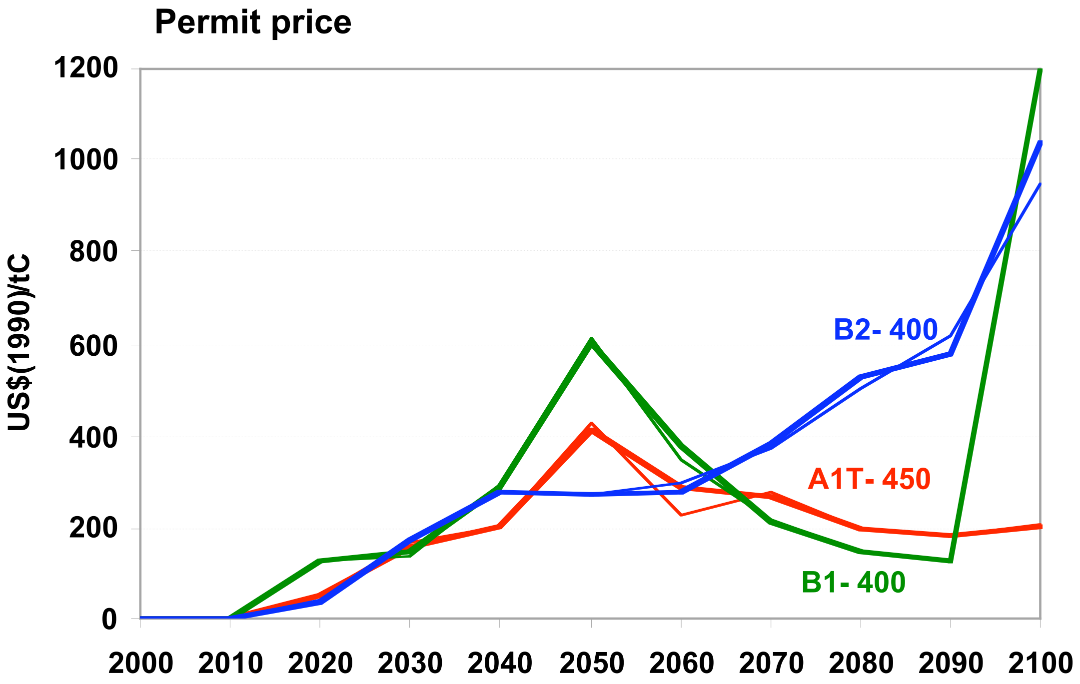

Figure 4.7: Carbon permit price for the six climate stabilization policy scenarios analyzed. Bold lines refer to the c&c2050 emission permit allocation scheme, thin lines to the c&c2100 allocation model. In constant 1990 US$ per tC.

A robust finding from the analysis reported here is that the marginal carbon abatement costs are quite close over the near term (to 2040) across the scenarios, gradually rising to some US200/tC. Between 2040 to 2060, a first bifurcation occurs in the price of carbon permits (marginal carbon abatement costs): Prices/costs remain low in scenarios in which zero-carbon options (e.g., nuclear) or carbon sequestration are unconstrained (B2-400 scenarios), but "spike" around 2050 for scenarios in which these options are assumed to be constrained (the B1-400 and A1T-450 scenarios incorporating e.g., the WBGU nuclear phaseout constraint). These scenario differences are gradually reduced by 2060, beyond which the base case scenario difference sets in. Costs/prices continue to rise in scenarios of a more modest outlook on the dynamics of new energy technologies (even if unconstrained) (B2-400 scenarios), whereas in scenarios with a more dynamic technology outlook, costs/prices remain comparatively low, to the tune of US$200/tC.[16]

The results also confirm the importance of exploring a wide range of baseline scenarios. For instance in considering only the technology optimistic, sustainable development baseline scenarios B1 and A1T could result in the misleading interpretation that the costs of meeting even extremely stringent climate stabilization goals are comparatively modest (some US$200/tC on average). This picture changes however drastically, when considering a more modest outlook on technology improvements as done in the B2 scenario, where costs continue to rise reaching some

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[16] The carbon permit price hike after 2090 in the B1-400 scenarios is due to the imposition of the WBGU constraint for carbon capture and sequestration assuming that the contribution of these technologies is zero from 2100 onwards. The model is flexible to chose an optimal deployment path for carbon capture under the given constraint, and is relying on this mitigation option until the very last moment when the constraint becomes binding (2100). To some extent the extreme price hike arises from modeling end-period truncation effects, and would presumably be less drastic, when the model calculations would be extended beyond 2100.

US$1,000/tC towards the end of the 21st century. This result confirms yet anew that an important element of any precautionary climate policy needs to pay particular attention to widening the portfolio of low cost abatement options (rather than constraining it). The larger the technology portfolio available, and the cheaper its costs, the easier (read: cheaper) it becomes to meet any (uncertain) ultimate climate stabilization target over the long term. Conversely, due to technological inertia, costs of meeting stringent climate stabilization goals are almost "pre-programmed" over the next couple of decades (i.e., are baseline scenario *in*dependent) and are essentially dependent on emissions constraints levels and existence (or absence) of flexibility mechanisms such as the international trade in carbon permits.

After having established the costs of meeting the carbon emission constraints assumed for the scenarios analyzed, we now can turn to the macroeconomic implications (costs) of climate stabilization. These costs include the costs of carbon emission reduction in a direct, narrow sense (e.g., through carbon sequestration and disposal), the costs of switching to more expensive alternative energy sources, the costs of energy conservation, as well as the macroeconomic costs (or benefits) of the resource transfers that go along with emission trading.

As mentioned above, the unique coupling of technology-rich engineering models with macroeconomic models achieved in the IIASA methodology results in a more balanced view of the macro-economic costs of climate stabilization at challenging low levels. Table 4.2 presents the numerical results.

Table 4.2 Change in regional GDP (compared to unconstrained baseline) of meeting climate stabilization targets of 450 ppmv (A1T) and 400 ppmv (B1, and B2) for two allocation schemes of carbon emission permits: c&c2050 and c&c2100 (in parentheses) for the years 2020, 2050, and 2100. In percent change compared to respective scenario baseline.

Change of GDP (% of baseline)		**OECD**	**REFS**	**ASIA**	**ALM**	**WORLD**
A1T-450	2020	-0.4 (-0.3)	0.8 (1.7)	-0.7 (-1.0)	-0.3 (-0.5)	-0.4 (-0.4)
	2050	-1.2 (-0.9)	-2.0 (-1.7)	-1.9 (-2.1)	-1.4 (-1.7)	-1.5 (-1.6)
	2100	-0.2 (-0.2)	-0.2 (-0.2)	-0.4 (-0.4)	-0.4 (-0.4)	-0.3 (-0.3)
B1-400	2020	-0.7 (-0.6)	0.3 (0.9)	-2.5 (-2.8)	-2.0 (-2.2)	-1.1 (-1.1)
	2050	-1.1 (-0.8)	-3.6 (-2.7)	-1.8 (-2.1)	-1.7 (-2.0)	-1.5 (-1.5)
	2100	-0.4 (-0.4)	-2.2 (-2.1)	0.1 (0.1)	-0.3 (-0.3)	-0.3 (-0.3)
B2-400	2020	-0.3 (-0.4)	-1.8 (-1.7)	-0.5 (-0.6)	-1.9 (-2.0)	-0.6 (-0.6)
	2050	-2.0 (-1.7)	-5.9 (-5.3)	-2.4 (-2.6)	-1.8 (-2.1)	-2.2 (-2.3)
	2100	-2.1 (-2.0)	-0.8 (-0.7)	-2.0 (-2.1)	-1.5 (-1.5)	-1.7 (-1.7)

This analysis that includes a full coupling of the costs of climate mitigation with the macro-economy confirms earlier observations on the importance of base case scenario assumptions. *Ceteris paribus,* macroeconomic costs for any given level of climate stabilization are higher in scenarios characterized by low economic productivity growth (GDP per capita) as well as in scenarios with a less dynamic technology outlook. This is clearly illustrated by the fact the scenario with the lowest GDP and the most conservative technology outlook analyzed here (B2) has the highest macro-economic costs of climate stabilization, both in absolute (US$) terms as well as in terms of percentage GDP losses.

An important finding of this analysis is the invariably[17] negative macro-economic effects of climate stabilization for all regions even after considering the impacts (losses/benefits) from emissions trading. Revenues from selling emissions credits are out-weighted by the costs of emission reductions even in developing countries. This obviously is a result of the stringent nature of the climate stabilization scenarios analyzed here, but it casts important doubts on the feasibility of full international cooperation for such strict climate regimes, unless it were possible to demonstrate that the economic losses from adverse climate impacts would exceed the numbers of GDP losses indicated in Table 4.2 for developing countries.[18] Especially noteworthy are the model results for the transition economies, in which GDP losses are generally in the longer term (2050) the highest among all regions concerned – and that for a region where the climate impact literature almost invariably suggests positive economic impacts of climate change.

Hence, more important than the absolute magnitude of the macroeconomic costs of climate stabilization, which given the ambitious stabilization goals are comparatively modest on a global scale, are issues of regional differences and disparities in balancing costs and benefits from climate change mitigation. In the aggregate the GDP loss of the climate stabilization ranges between 0.3 to 1.7 percent of GDP, which means of resetting the global economic output in the year 2100 to the value prevailing in the year 2099, which is not a daunting perspective indeed (even if a comparison in absolute numbers of the future GDP loss to current GDP would yield rather an impressive figure[19]). The fact, that the estimates reported here are at the low end of the comparable literature (drawing mostly on the results of macro-economic models) and that we feel confident about these results, is yet another illustration of the benefits of a comprehensive methodological framework that integrates both systems engineering and macro-economic model perspectives. And yet, even our comparatively optimistic global outlook confirms the importance of looking into the details of regional disparities in the burden sharing of the costs of combating climate change. Unless more satisfactory burden sharing schemes for transition economies and developing countries can be devised than analyzed here, there remain important doubts on the political and economic feasibility of stringent climate stabilization scenarios that put a proportionally higher economic burden on those that have not caused the problem in the first place.

4.3.4 Emission reduction measures

Figure 4.8 summarizes the various measures for emission reduction at the global level based on the model results obtained with the coupled MESSAGE and MACRO models. The multitude of emission reduction measures are summarized under three major categories for ease of comparison: energy demand reduction (conservation induced by rising energy prices due to the carbon constraints); structural change (primarily inter-fuel substitution either within fossil fuels, e.g., substitution of coal by natural gas use, or between fossil fuels and non-fossils, i.e., renewables in this case);

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[17] The only exception being the region Asia for the year 2100 in the B1-400 scenario, where modest economic gains are indicated.

[18] Based on the available climate impact literature this seems a difficult proposition indeed as GDP losses from developing countries due to climate stabilization typically range between one to two percent of GDP in the scenarios analyzed, whereas the literature on *market impacts* suggests typical values of negative climate change impacts below one percent of GDP in developing countries.

[19] Depending on the scenario analyzed the GDP loss by 2100 amounts to between 1 (B1-400) to 4 (B2-400) Trillion $ (constant 1990 US$) compared to a world GDP in the year 2000 of some 27 trillion $ and a respective world GDP by 2100 of between 235 (B2) to 529 (A1T) trillion $.

and finally carbon capture (scrubbing) and storage (sequestration). It should be noted that in this study only carbon emissions from industrial sources were considered as potential target for emission reductions, as insufficient information is currently available to estimate detailed emission reduction costs for non-industrial sources or for GHGs outside carbon.

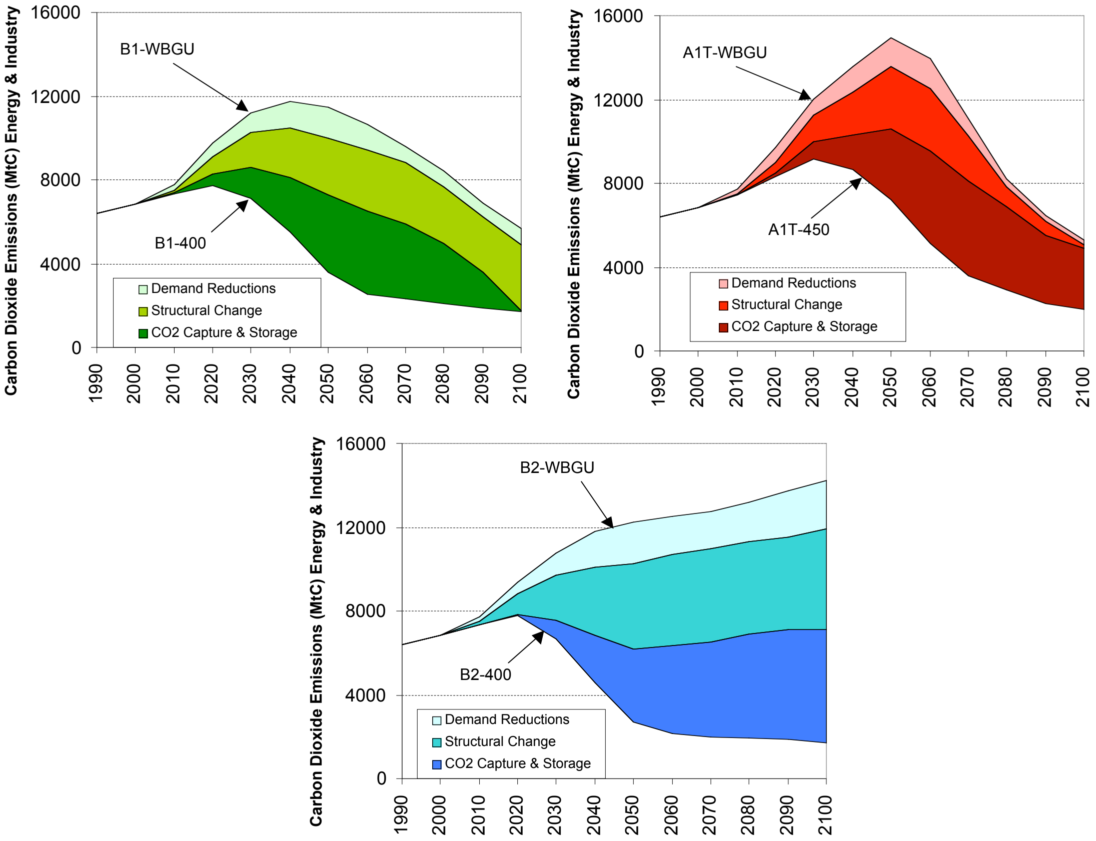

Figure 4.8: Magnitude of emission reductions between unconstrained baseline and climate stabilization scenarios, by type of measures. In MtC (Million or mega tons of elemental carbon).

Depending on the baseline scenario, existence of additional WBGU constraints on zero-carbon options and carbon capture (for scenarios B1 and A1T), as well as ultimate stabilization target to be achieved (450 ppmv for A1T and 400 ppmv for the other two scenarios), the relative importance of mitigation measures varies across the scenarios. Overall, demand reductions due to rising energy and carbon prices are of lesser importance compared to structural change and carbon sequestration, as the overall costs of meeting the stabilization targets remain comparatively modest. (For the scenario with much higher costs (B2-400) energy conservation plays consequently a much larger role.) The second differentiation between the scenarios concerns the role of carbon sequestration versus other interfuel substitution measures. In case carbon capture is assumed to be constrained (B1-400 scenario) this technological option is a transient one (cf. Figure 4.8); in case the option is unconstrained, carbon capture plays an important role in the mitigation technology portfolio throughout the 21st century.[20]

Given these findings structural changes in the energy supply chains assume a dominant role in the WGBU scenarios, particularly in the B2 scenario in which the baseline scenario describes more modest structural changes compared for instance to the rather extreme A1T scenario that postulates already a secular transition away from fossil fuels already in the base case scenario without climate change (cf. Figure 4.9).

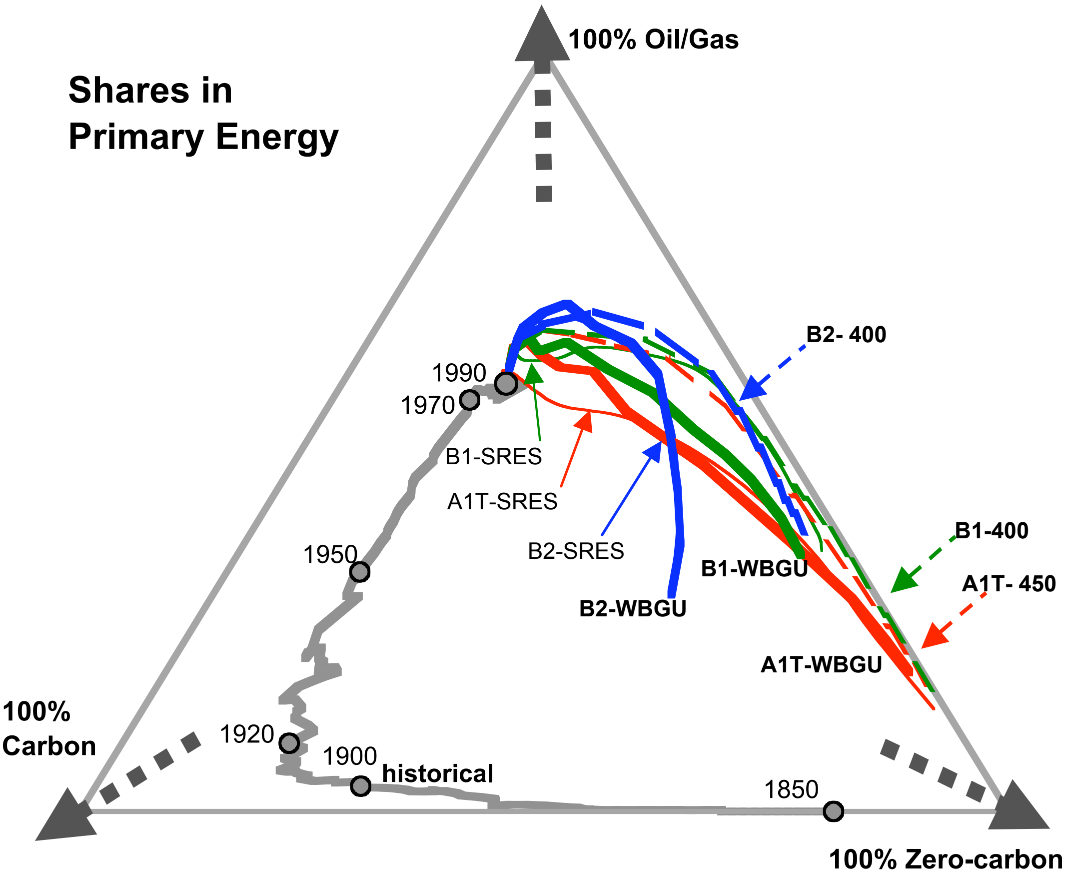

Figure 4.9: Energy triangle. Share of coal, oil/gas, and zero-carbon options in global primary energy supply: Historical (since 1850) and in the scenarios analyzed in this study to 2100. Note in particular the similarity of almost all scenarios in terms of their primary energy structure towards the end of the 21st century resulting from the relatively limited choice of three baseline scenarios and the stringent climate stabilization targets adopted. In percent.

The fact that two of the three base case scenarios as well as invariably all the three climate stabilization scenarios display such similar structural changes in energy supply is related to the assumptions of this study concerning choice of base case scenarios as well as technological constraints. The resulting technological “monoculture” can be considered both a limiting factor of the analysis presented here (as illustrating a too constrained choice of base case scenarios, compressing uncertainty), but at the same time also an interesting signal for energy technology

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[20] Note that without unconstrained carbon sequestration a 400 ppmv stabilization scenario imposed upon the SRES-B2 scenario with its more moderate technology dynamics would be infeasible.

policy that has to date largely ignored the risks associated with technological “lock-in” in a few critical energy technologies. It is almost ironic that present arguments for energy sector diversification that should favor a larger share of renewables in the energy portfolio could in the distant future be turned against renewables themselves, at least in scenarios that follow the lines of the (admittedly) extreme examples illustrated here.

The most important renewable “backstop” technologies constitute intermittent renewables for electricity generation (PV and wind) as well as solar hydrogen, of critical importance for the transportation energy demands. These technologies, while disposing of the highest “option value” for climate stabilization in the scenarios analyzed, are at the same time those technologies, that if turning out as infeasible at the scale described by the scenarios pose the most serious risk of not attaining the desired climate stabilization levels. Therefore, these critical technological options should be analyzed in much more detail in future with respect to technological and economic feasibility as well as potential environmental impacts. This early, anticipatory technology assessment is considered as an important element of any enhanced research and development (R&D) strategy for climate friendly energy technologies.

4.4 Limitations of the Analysis

After presenting the study’s main results and findings it may be also useful to summarize the main limitations of the analysis that need to be borne in mind before drawing definitive policy conclusions. The robustness of the study findings in particular are limited by a number of factors, most notably:

- The limited number of base scenarios analyzed, that artificially compresses uncertainty;
- The use of a singular burden sharing scheme in distributing emission permits, again compressing uncertainty as well as reducing the likelihood of the climate stabilization scenarios (lack of potential buy-in from developing countries);
- The large number of constraints imposed on future energy technologies, significantly reducing the portfolio for low or zero-carbon technologies. This increases the vulnerability (and decreases the likelihood of feasibility of the climate stabilization scenarios) in case one of the dominant energy sector “backstop” technologies (most notably solar hydrogen and to a lesser degree decarbonization of hydrocarbon sources of energy) should prove infeasible for technological, economic, or ecological reasons.

Finally, whereas above limitations of the analysis reported here can be remediated by additional, in-depth studies of a larger set of scenarios, burden sharing schemes, and extensive energy technology portfolio analysis, there remain also important limitations inherent to the study methodology deployed (and for which no practical alternatives are available in the literature yet):

- The main methodological limitation of the present study relates to both the methodological nature of inter-temporal optimization models assuming both a social planner operating under perfect foresight with no uncertainty (e.g., on the ultimate climate stabilization target) as well as under perfectly functioning global markets (enabling to separate neatly issues of equity and efficiency, and ignoring the important problem of possible un-cooperative behavior or “free-riding”).

We address above four areas of limitations in more detail below.

1. Limited number of base case scenarios

In this study three base case scenarios served as background scenarios to analyze feasibility, costs, and trade flows of ambitious climate stabilization targets. Two of these scenarios, based on the IPCC SRES-B1 and A1T scenarios, are in fact structurally quite close. Both scenarios explore different dimensions of sustainable development, with an emphasis of closure of the North-South development gap and the rapid development and diffusion of post-fossil technologies. Only one scenario, based on SRES-B2, adopts a more “moderate” (or pessimistic) outlook. Whereas all three scenarios are interesting and valuable, they nonetheless constitute a too limited base to judge feasibility and costs of ambitious climate stabilization as artificially reducing the large uncertainties inherent in projection a multitude of developments some hundred years out into the future.

Another factor has constrained the choice of available background scenarios in this study. The significant constraints imposed on zero-carbon options in the stabilization scenarios have meant that practically only a single original SRES scenario was consistent with both a 400 ppmv stabilization scenario as well as the WBGU zero-carbon technology constraints (with the A1T conditionally consistent, and the B2 scenario only feasible without WBGU constraints.) Thus there is an inherent tradeoff existing between exploring uncertainties of scenario baselines along with uncertainties of technology constraints. Both uncertainty spaces cannot be explored together at their extreme end distributions (e.g., high emission scenarios with stringent technology constraints but under ambitious climate stabilization targets), leading to a compression in base case scenario uncertainty.

It has been a frequent observation in the literature (e.g., Roehrl and Riahi, 2000), that for climate policy baseline scenario differences are more important in determining feasibility and costs of climate stabilization than the ultimate level of the stabilization goals. In other words, it matters more in which different future world climate policies are assumed to be implemented, than the degree of ambition these climate policies pursue (400 ppmv or even 550 ppmv stabilization). For both scenarios A1T and B1, the 400-450 ppmv stabilization targets are both achievable comparatively easily and at comparatively modest costs (generally below US$200/tC).[21]

This illustrates the multiple benefits of sustainable development scenarios, but it also provides for a potential pitfall in climate change policy, namely to assume that policies can easily be implemented *assuming* that everything else is also developing in the right direction. Conversely, a critical question of uncertainty remains: are these climate stabilization targets and policies as feasible and cheap in case the world would not move uniformly in the direction described by sustainable development scenarios?

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[21] We speak of “comparatively easily” achievement of the stabilization targets especially considering the additional constraints imposed on zero-carbon energy technologies (nuclear and biomass) as well as carbon sequestration assumed for these WBGU scenarios. These constraints show up as “spikes” in the carbon permit price around the year 2050 (reaching 600 $/tC) in all scenarios due to the nuclear phase-out constraint and around 2100 (reaching some 1200 $/tC) due to the carbon sequestration constraint in B1-400. But these price hikes are transient phenomena.

The answer obviously is not, as for instance indicated by the costs of meeting an equally stringent target in a world as described by the SRES-B2 scenario (where costs could easily rise beyond US$1,000/tC). Therefore, a wider set of scenarios would need to be analyzed (including for instance also examples from the SRES-A2 scenario family) to avoid an unjustified sense of optimism or complacency. After all, the multiple dimensions of sustainable development and the key question of what constitutes a sustainable development scenario are even more contentious and uncertain than extent, and timing of climate policies. From this perspective one could argue that scenarios of climate stabilization might be easier to be agreed upon and implemented internationally than scenarios of comprehensive sustainable development.

2. Use of a single burden-sharing scheme

The burden sharing scheme analyzed here has – like all alternative schemes – a number of advantages as well as disadvantages as discussed in Section 4.2 above. Given that a wide international agreement would be necessary before such a burden sharing scheme could come into operation, the potential objections to such a scheme from both the perspectives of the "North" as well as the "South" need careful consideration. For instance, Annex-I countries may quite legitimately object to any per capita allocation criterion as proving an incentive for unfettered population growth. Conversely, non-Annex-I countries quite legitimately might object the fact that historical responsibility in creating the climate change externality remains ignored, as well as that the resulting emission permit allocation leads to an aggravation in the North-South disparities in GHG emissions. It was observed in Section 4.2 that the particular allocation scheme analyzed gives Annex-I countries an even higher share in global emissions, than in case of their unconstrained base case scenarios.

Evidently, no individual burden sharing scheme is likely to be ever developed that will find universal appeal. It seems therefore even more important to inform the policy debate by a systematic analysis of a number of alternative burden sharing schemes on potential sources of conflict, but also on potential areas of confluence of interests. Such an analysis certainly should also include "transitional" burden sharing schemes, e.g., schemes that combine a variety of allocation principles and criteria, depending on timing and development status of the respective parties involved. For instance, a pragmatic approach could start from an allocation scheme combining elements of emission status quo ("grandfathering") with a gradual phase in of emission reduction proportional to historical responsibility, finally to gradually phase in per capita emission entitlements as additional criteria. The fact that it was not possible in this study to systematically explore alternative emission allocation schemes therefore remains an important shortcoming and constitutes a priority area for future research.

3. Constrained technology portfolios

Combined with the choice of only a limited number of base case scenarios, the imposition of a larger number of additional constraints (compared to the original IPCC SRES scenarios) on the potential supply of zero-carbon energy or of carbon sequestration constrains the technology portfolios analyzed in this study significantly. This does not reduce the soundness of any individual scenario explored as being consistent with latest theories of path dependency in technological systems (see e.g., Arthur, 1989, Grübler, 1998) but constitutes a limitation across the range of scenarios explored as resulting in a significant reduction of the technological diversity future climate policy initiatives can draw upon and in considering full uncertainty. It also increases vulnerability of any particular climate stabilization regime in cases the dominant technologies options carrying the backbone of the energy system in the scenarios explored here (intermittent renewables and solar hydrogen in particular) would turn out infeasible at the scale assumed in the scenarios due to economic, technological, or environmental reasons.

Thus, the analysis of the potential "option value" of various technological systems for climate stabilization scenarios is limited given the constrained technology portfolios analyzed in this study. Analysis of a wider range of technology options as well as addressing the issue of spatial heterogeneity, in which certain technologies (e.g., nuclear) could be banned in some regions, but furthered in others with different resource endowment conditions, remains thus an important future research task.

4. Methodological limitations

As mentioned above, a main methodological limitation (which as inherent in the status quo of available methodologies not only applies to the present study, but to almost the entirety of the climate change policy literature) is the potential mismatch in the main assumptions on existence of a social planner, perfect foresight, and no uncertainty underlying the modeling and economic calculus of climate policy scenarios. This study (as well as the bulk of the relevant literature) has also assumed the existence of perfectly functioning global markets in emission permits, allowing for equalization of regionally diverse marginal emission reduction costs. Evidently, decision making in the real world is far more complex and fuzzy than these simplifying modeling assumptions suggest. As is evidenced for instance by the on-going discussion on the Kyoto Protocol, the modalities for crediting joint implementation measures or investments under the clean development mechanism continue to be under discussion, and the perspective of an emerging global functioning market on emission permits after 2010 (as assumed in this study) seems challenging to say the least. If any of above mentioned assumption is relaxed, feasibility of climate stabilization declines and costs of meeting climate targets increase. The results presented here should therefore be interpreted as minimum cost estimates under an optimistic implementation outlook, ignoring important aspects of potential uncooperative behavior and of free-riding under any climate stabilization regime. An important research task remains therefore, to extend both analysis and models in direction of uncertainty, imperfect information, and heterogeneous agents with potentially non-cooperative behavior.

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