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Interim Report **IR-10-019**

Emissions of air pollutants implied by global long-term energy scenarios

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Contents

Abstract

This report presents a methodology to link national medium-term (up to 2030) with global long-term (beyond 2050) emission scenarios. Such a linkage is relevant for estimating impacts of global long-term climate change scenarios on local and regional air pollution in the next few decades.

We present a methodology for the linkage that combines results from two models developed at IIASA: the GAINS air pollution model and the MESSAGE model of long-term energy system dynamics. We calculate for energy scenarios developed by the MESSAGE model future emissions of air pollutants (SO_2, NO_x, PM, BC/OC, NH_3, VOC and CO), taking into account air pollution control legislation that is in place in the various countries.

Example results are provided for the “middle-of-the-road” B2 baseline scenario. Under the B2 scenario global emissions of sulfur, nitrogen oxides and carbon monoxide decline continuously between 2000 and 2100, largely due to widespread implementation of air pollution control technologies. On the other hand, in Asian developing countries sulfur emissions will increase significantly up to 2030 due to the strong increase in coal use for power generation. In contrast, a climate stabilization scenario highlights synergies from the co-control of air pollutant and greenhouse gas emissions. Finally, the role of shipping emissions is discussed within the global context, and resulting emission projections are compared with other analyses.

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Emissions of air pollutants implied by global long-term energy scenarios

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1 Introduction

Many of the traditional air pollutants and greenhouse gases have common sources. Thereby, emission reduction measures that are directed at greenhouse gases have simultaneous impacts on air pollutants, and vice versa. This co-control of multiple pollutants yields co-benefits that must not be overlooked when assessing benefits of mitigation strategies. It also opens the way for more cost-effective emission control strategies through concurrently managing traditional pollutants and greenhouse gases. It is therefore of particular importance to develop methodologies that allow for a quantitative assessment of potential synergies between mitigating climate change and other goals of sustainable development such as air pollution.

However, as the impacts of air pollution and climate change emerge at different spatial and temporal scales, scientific analyses of these problems are traditionally conducted by different communities with different tools. In particular, computer models that are used to develop global long-term scenarios of future greenhouse gas emissions address emissions of air pollutants only in an aggregated manner. In many cases these tools lack much of the technological detail that is necessary for an accurate assessment of air pollutant emissions. Vice versa, the tools that estimate future emissions of air pollutants are often restricted to the next few decades and capture the wealth of technological information only for limited geographical areas.

A few analyses of the future global development of air pollutant emissions for the coming decades have been developed by IIASA using the RAINS/GAINS modeling framework (Cofala et al., 2006, Cofala et al., 2007a). These studies investigated the impacts of recently introduced legislation on air pollution emissions at the global scale, and explored by how much emissions could be further reduced through full application of currently available technical emission control measures. As these bottom-up studies were based on national projections of future energy use, the lack of national long-term projections limited their time horizon to 2030.

Other IIASA studies have investigated how emissions of air pollutants may change in the long run. Using the global energy system MESSAGE model, global emission scenarios for the 21st century have been developed by Nakicenovic et al. for the IPCC (2000) and updated by Riahi et al. (2007). While these scenarios were primarily developed for examining the dynamics of the energy system in the long run and the resulting impacts on greenhouse gas emissions, they also provide some indication of how air pollutants (e.g., SO_2) may be affected by the changes in the energy system. However, the SRES calculations did not include other relevant air pollutants such as NO_x, CO, PM, NH_3 or VOC, and excluded the impacts of the fast changing legislation on air pollution emissions. Also Riahi et al, 2007 assumed increasing stringency of control legislation for SO_2, NO_x, BC, and OC, but not for other emissions.

Thus, the currently available tools do not allow estimating air pollution emissions with the required technological detail at the global scale and for time horizons that are relevant for climate mitigation strategies.

This paper presents a methodology to derive such global estimates for the greenhouse gas emission scenarios that are presently discussed within the climate change community. The methodology combines information on the global long-term trends of the drivers of air pollution emissions, i.e., projections of future fuel consumption, with detailed information on local emission control technologies, national legal regulations and fuel quality.

To estimate long-term trends of a wide range of air pollutants at the global scale, we combine scenarios of the drivers of emissions developed with IIASA's MESSAGE energy system model with in-depth information on national emission characteristics provided by IIASA's GAINS model.

The remainder of this paper is organized as follows. Section 2 reviews the relevant methodologies of the MESSAGE and GAINS models and presents the methodology for linking emission calculations across temporal and spatial scales. Section 3 introduces calculations for two global emissions scenarios, i.e., the B2 baseline scenario and a scenario which stabilizes GHG concentrations in the atmosphere at 450 ppm. Section 4 discusses specific details for international shipping. Conclusions are drawn in Section 5.

2 Methodology

In this study, information from two models, GAINS and MESSAGE, is combined to quantify the impacts of long-term global GHG-mitigation efforts on air pollution emissions in 11 world regions. The analysis considers emissions of SO_2, NO_x, PM, CO, BC, OC, NH_3 and VOC, and how the anticipated changes in future activity levels combined with progressing implementation of national emission control legislation will impact these emissions.

The approach described in this report has been used for a limited set of pollutants (CO and NO_x) for developing long-term emission scenarios of ozone precursors (Royal Society, 2008) and for long-term scenarios of black and organic carbon emissions (Rao et al., 2005). For the Representative Concentration Pathways (RCP) scenarios of the Intergovernmental Panel on Climate Change (IPCC, 2007), an early version of the approach has been employed to calculate associated emissions of SO_2, NO_x, VOC, CO, BC, OC, NH_3.

2.1 The GAINS model

The GAINS (Greenhouse gas – Air pollution Interactions and Synergies) model has been developed as a tool to identify emission control strategies that achieve given targets on air quality and greenhouse gas emissions at least costs. It quantifies the full DPSIR (demand-pressure-state-impact-response) chain for the emissions of air pollutants and greenhouse gases. Thereby it represents an extension – and a practical implementation - of the pressure-state-response model developed by the OECD. GAINS incorporates data and information on all the different elements in the DPSIR chain and specifies connections between these different aspects. In particular GAINS quantifies the DPSIR chain of air pollution from the driving forces (economic activities, energy combustion, agricultural production, etc.) to health and ecosystems effects (Figure 1).

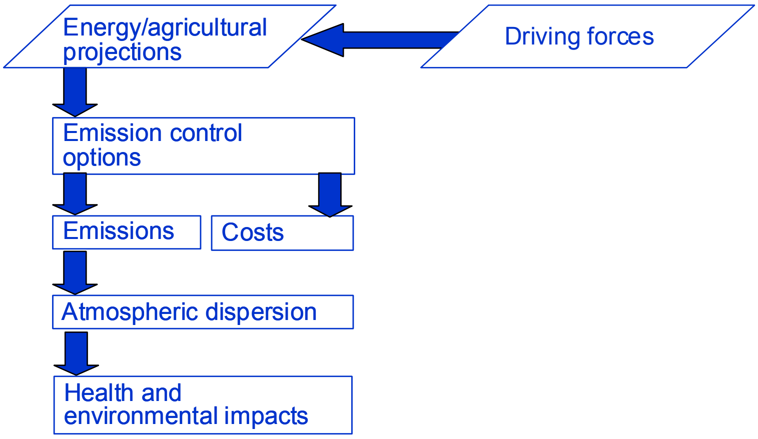
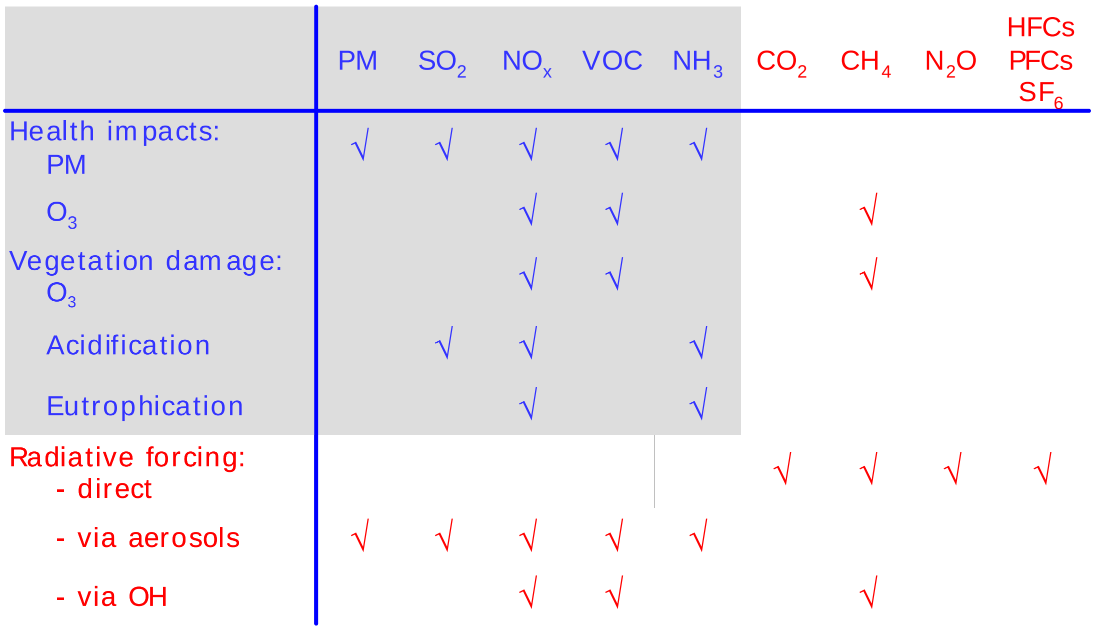


Figure 1: DPSIR chain of the GAINS model for the emissions of greenhouse gases and air pollutants

GAINS captures the multi-pollutant/multi-effect nature of atmospheric pollution. It addresses impacts of air pollution on human health, vegetation and aquatic ecosystems, and considers the release of emissions that exert radiative forcing. GAINS follows emissions of sulphur dioxide (SO_2), nitrogen oxides (NO_x), various fractions of fine particulate matter (PM), ammonia (NH_3) and volatile organic compounds (VOC). In addition, GAINS includes the greenhouse gases carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and the F-gases HFC, PFC, SF_6 (Figure 2).

GAINS considers measures for the full range of precursor emissions that cause negative effects on human health via the exposure of fine particles and ground-level ozone, damage to vegetation via excess deposition of acidifying and eutrophying compounds, as well as the six greenhouse gases considered in the Kyoto protocol. In addition, it also assesses how specific mitigation measures simultaneously influence different pollutants. Thereby, GAINS allows for a comprehensive and combined analysis of air pollution and climate change mitigation strategies, which reveals important synergies and trade-offs between these policy areas.



	PM	SO_2	NO_x	VOC	NH_3	CO_2	CH_4	N_2O	HFCs PFCs SF_6
Health impacts: PM	√	√	√	√	√				
O_3			√	√			√		
Vegetation damage: O_3			√	√			√		
Acidification		√	√		√				
Eutrophication			√		√				
Radiative forcing: - direct						√	√	√	√
- via aerosols	√	√	√	√	√				
- via OH			√	√			√		

Figure 2: The GAINS multi-pollutant/multi-effect framework

GAINS quantifies the technical and economic interactions between mitigation measures for the considered air pollutants and greenhouse gases. It assesses the simultaneous impacts of emission reductions on air pollution (i.e., shortening of statistical life expectancy due to population exposure to PM2.5, premature mortality related to ground-level ozone, protection of vegetation against harmful effects of acidification and excess nitrogen deposition) as well as for selected metrics of greenhouse gases (e.g., global warming potentials). Thus GAINS explores the full effect of reducing air pollutants and/or greenhouse gases on all these endpoints. In addition, GAINS includes an optimization approach that allows the search for least-cost combination of mitigation measures for air pollutants and/or greenhouse gases that meet user-specified constraints (policy targets) for each of the environmental endpoints listed above. Thereby, GAINS can identify mitigation strategies that achieve air quality and greenhouse gas related targets simultaneously at least cost.

The GAINS model (http://gains.iiasa.ac.at) is currently implemented globally on regional, national or provincial levels for 45 countries in Europe, for the Annex I countries of the Kyoto Protocol, for fast growing economies of China and India, as well as for remaining countries in the East and South Asia, Africa, Middle East and South America. It covers the time horizon up to 2030.

In the stand-alone GAINS model, emissions E of an air pollutant in a country i are calculated as the product of energy activity levels A in a sector s consuming a fuel f, multiplied by the "uncontrolled" emission factor EF in absence of any emission control measures, a factor eff adjusting for the removal efficiency of emission control measures m, and the application rate X of such measures.

$$E_i = \sum_{s,f,m} E_{i,s,f,m} = \sum_{s,f,m} A_{i,s,f} * EF_{i,s,f} * (1 - eff_m) * X_{i,s,f,m}$$

Activity rates A are exogenous input to the GAINS model, derived from external energy projections or, for the purposes of this study, from the energy scenario developed with the MESSAGE model.

The set of parameters EF, eff and X defines a "control strategy" that reflects the level of implementation of specific emission control measures in a country at a given time. The GAINS database contains information about several hundreds of abatement measures in numerous sectors, applicable to a range of activities of fuel types.

Through the time-dependent implementation rates X of specific emission control measures the GAINS model reflects the penetration of mitigation measures in each country, e.g., as prescribed by national air quality regulations. The technical and economic descriptions of available emission control measures as well as their country-specific implementation schedules focus on the time period up to 2030.

2.2 The MESSAGE model

The underlying projections of energy activities that determine the levels of GHGs and air pollutants are provided by MESSAGE, an engineering "bottom-up" optimization model (http://www.iiasa.ac.at/Research/ENE/model/message.html) used for medium- to long-term energy system planning, policy analysis and scenario development (Nakicenovic et al., 1998). The IIASA MESSAGE model represents 11 world macro-regions with a time horizon of 100 years. The application of MESSAGE that is used in this report for the analysis of long-term climate stabilization scenarios is reported in Riahi et al., 2007.

The MESSAGE model provides a framework for representing an energy system with the most important interdependencies. The basic energy flows are covered starting 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 version used herein provides information on the utilization of domestic resources, energy imports and exports, trade-related monetary flows, investment requirements, types of production or conversion technologies selected (technology substitution), 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. Scenarios presented in this report are based on the disaggregated global energy system model consisting of 11 regions, covering both industrialized and developing countries. Consistent with the focus on long-term climate protection strategies, the MESSAGE scenarios use a time horizon from 1990 to 2100.

The multi-regional MESSAGE model is constructed by specifying performance characteristics of a set of technologies and defining a reference energy system (RES) for each region that includes all the possible energy chains that the model can use. In the course of a model run, MESSAGE 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. For more details on the model and the mathematical representation of the RES see Messner and Strubegger (1995).

The optimization module of MESSAGE identifies the configuration of the energy system that satisfies the exogenously supplied end-use demand at least cost. Cost components include investments, operation and maintenance cost, fuel cost, and emission control cost and/or taxes. The function used in MESSAGE to determine the present value of total cost over the whole computational period is called objective function. A discount rate of 5% is used in the scenario calculations presented here.

2.3 The linkage between MESSAGE and GAINS

A methodology has been developed to link mid-term emission projections of air pollutant emissions derived by GAINS for individual countries with long-term energy projections that are developed with MESSAGE for a limited number of world regions. The link reported in this paper is a part of the Integrated Assessment Framework developed and implemented at IIASA. The flow of information between main components of the integrated assessment tools is shown in Figure 3.

The basic rationale of the linkage aggregates country-specific information on emission characteristics that is provided by GAINS for the time period up to 2030 into corresponding information for the 11 world region for which the MESSAGE model calculates long-term energy scenarios up to 2100. Thereby, long-term scenarios of air pollutant emissions employ, for each of the world regions considered, the fuel consumption projections of the MESSAGE model together with country-scale information on emission characteristics (i.e., emission factors for different fuel uses, technological and economic information on the performance of emission control measures, implementation rates of emission control measures, shares of individual countries in the total fuel consumption of the considered world region). The long-term evolution of the implementation of emission control measures as well as technological progress in the performance of emission control technologies is considered as additional information in the development of emission scenarios.

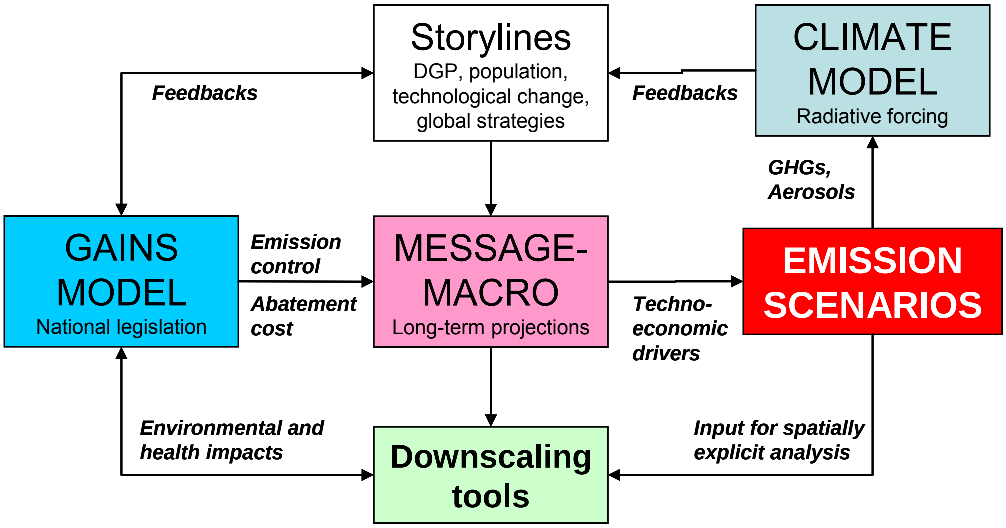


Figure 3: Relationship and information flow between models.

For this approach the country-specific GAINS information needs to be aggregated into the set of world regions of the MESSAGE model. The aggregation scheme is presented in Table 1.

Table 1: Mapping of MESSAGE and GAINS regions.

Acronym	MESSAGE Regions	GAINS Regions
AFR	Sub-Saharan Africa	Other Africa, South Africa
CPA	Centrally planned Asia and China	Cambodia, China (incl. Hong Kong), Korea (DPR), Laos (PDR), Mongolia, Viet Nam
EEU	Central and Eastern Europe	Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Macedonia, Hungary, Poland, Romania, Slovak Republic, Slovenia, Serbia and Montenegro
FSU	Newly independent states of the former Soviet Union	Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Republic of Moldova, Russian Federation, Ukraine, Other USSR Asia
LAM	Latin America and the Caribbean	Argentina, Brazil, Chile, Mexico, Other Latin America
MEA	Middle East and North Africa	Egypt (Arab Republic), Middle East, North Africa
NAM	North America	Canada, United States of America
PAO	Pacific OECD	Australia, Japan, New Zealand
PAS	Other Pacific Asia	Brunei Darussalam, Indonesia, Malaysia, Myanmar, Philippines, Republic of Korea, Singapore, Taiwan (China), Thailand
SAS	South Asia	Afghanistan, Bangladesh, Bhutan, India, Nepal, Pakistan, Sri Lanka
WEU	Western Europe	Austria, Belgium, Cyprus, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Malta, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom

In addition to the spatial aggregation, the methodology also groups physical, technological and institutional characteristics of emission sources of individual countries that are explicitly considered in GAINS to match the more aggregated level of detail of the MESSAGE model. For this purpose, **abated emission factors** are defined as appropriate linkages. For each MESSAGE world region such abated emission factors (*AEF*) are derived for the all sector-fuel combinations provided by the MESSAGE model (Table 2). For 2030 they are calculated from the GAINS emission scenarios by dividing total emissions calculated by GAINS by the corresponding activity levels considered in MESSAGE:

$$AEF_{i,s,f,y}^{MESSAGE} = \frac{E_{i,s,f,y}^{GAINS}}{A_{i,s,f,y}^{GAINS}}$$

Table 2: Mapping of major emission source categories of the MESSAGE and GAINS models.

MESSAGE fuel/sector		←	GAINS fuel	GAINS sector			
Residential and Commercial	biomass_rc	←	OS1 OS2	Domestic (DOM)			
	coal_rc	←	HC1 HC2 HC3 BC1 BC2 DC				
	gas_rc	←	GAS				
	loil_rc	←	MD GSL LPG				
	foil_rc	←	HF				
	eth_rc	←	ETH				
	meth_rc	←	MTH				
	h2_rc	←	H2				
Industry	biomass_i	←	OS1 OS2	Industry combustion (IN_OC)	Industry boilers (IN_BO)	Off-road machinery and construction (TRA_OT_CNS)	
	coal_i	←	HC1 HC2 HC3 BC1 BC2 DC				
	gas_i	←	GAS				
	loil_i	←	MD GSL LPG				
	foil_i	←	HF				
	eth_i	←	ETH				
	meth_i	←	MTH				
	h2_i	←	H2				
Transport	coal_trp	←	HC1 HC2 HC3 BC1 BC2 DC	Road (TRA_RD_LD2, TRA_RD_M4, TRA_RD_LD4C, TRA_RD_LD4T, TRA_RD_HDT, TRA_RD_HDB)	Off-road (TRA_OT_LD, TRA_OT_LB, TRA_OT_AGR, TRA_OT_RAI)	Aviation (TRA_OT_AIR)	Shipping (TRA_OT_INW, TRA_OTS)
	gas_trp	←	GAS				
	loil_trp	←	MD GSL LPG				
	foil_trp	←	HF				
	eth_ic_trp	←	ETH				
	meth_ic_trp	←	MTH				
	h2_ic_trp	←	H2				
Non-enenrgy uses	coal_fs	←	HC1 HC2 HC3 BC1 BC2 DC	Non-enenrgy uses (NONEN)			
	gas_fs	←	GAS				
	loil_fs	←	MD GSL LPG HF				
	foil_fs	←	HF				
	eth_fs	←	ETH				
	meth_fs	←	MTH				
Power & heat plants incl. CCS	bio_ppl	←	OS1	Existing power plants (PP_EX_OTH)	New plants (PP_NEW)		
	mw_ppl	←	OS2				
	gas_ppl	←	GAS				
	loil_ppl	←	MD GSL LPG				
	foil_ppl	←	HF				
	coal_ppl_u	←	HC1 HC2 HC3 DC BC1 BC2				
	coal_ppl	←	HC1 HC2 HC3 DC BC1 BC2		New plants (PP_NEW)		
	coal_adv	←	HC1 HC2 HC3 DC BC1 BC2				
	igcc	←	HC1 HC2 HC3 DC BC1 BC2	IGCC plants (PP_IGCC)			
Own use and transformation	extraction_coa	←	HC1 HC2 HC3	Conversion combustion (CON_COMB)			
	extraction_gas	←	GAS				
	extraction_oil	←	HF				
	lignite_extr	←	BC1 BC2				
	ref_hil	←	HF		Refineries (PR_REF)		
	ref_lol	←	HF				

In the above formula abated emission factors are computed for the period until the year 2030, i.e., the latest year for which GAINS provides detailed information. However, the question how such emission factors will change in the long run after 2030, cannot be answered in an unambiguous way as it is influenced by the rate of technological progress on emission control measures and deliberate changes in national air quality legislation.

As neither the GAINS nor the MESSAGE models hold information on these aspects, the long-term evolution of these factors has to be specified exogenously as additional scenario variables. Ideally, such assumptions should be coherent with the general story line that underlies a particular long-term energy scenario (e.g., about technological progress and the societal value of sustainable air quality and environmental protection).

While a wide range of developments is conceivable, the likely range of trends in emission factors could be constrained by two cases:

(i) a pessimistic assumption that technologies and legislation would not change beyond 2030, and

(ii) a more optimistic assumption that emission standards (of new built equipment) in each country would converge over time to today's world best available technology. These technology improvements should not be interpreted as an autonomous change, but require dedicated policies to strengthen air quality legislation beyond present plans.

To illustrate the range of emissions resulting from the two approaches listed above, two scenario variants are reported in the following sections. First, the baseline case B2 CLE 2030, where the current legislation (CLE) is adopted and emission factors remain fixed beyond 2030:

$$AEF_{i,s,f,y>2030} = AEF_{i,s,f,y_{2030}}$$

In the second scenario B2 CLE GDP, emission coefficients are scaled proportionally with the time evolution of GDP-per-capita in the respective MESSAGE region for a given baseline scenario after 2030. In the long run, emission factors converge across regions following the assumption that the higher environmental quality will be associated with increasing welfare.

$$AEF_{i,s,f,y} = AEF_{i,s,f,y_{2030}} * \frac{GDP^{CAP}_{y_{2030}}}{GDP^{CAP}_{y}}$$

At the same time, the calculation algorithm assures that the abated emission factor for any region will not shrink below the levels that are today achievable through implementation of best available abatement technology for a given pollutant.

$$AEF^{CLE}_{i,s,f,y} \leq AEF^{MFR}_{i,s,f,y}$$

Appendix I contains an example of the SQL-code for the computation routine used to derive a set of implied NO_x emission factors in the MESSAGE aggregation, while adopting the CLE short-term measures from the GAINS model databases.

It should be the noted that the energy scenarios underlying the GAINS and MESSAGE models are independent, i.e., no attempt has been made to link the energy system activities in the two models for the year 2030. Linkages are only established at the level of emission abatement measures. While future energy use in both the original SRES scenarios and the updated GGI B2 scenario are a result of the optimization of the MESSAGE model, energy projections in GAINS are exogenous and originate mainly from national energy planning. Methodologies to endogenize the interchange of activity data between GAINS and MESSAGE have been explored and reported earlier by Rafaj et al. (2008).

Merging the activity projections would imply that long-term MESSAGE projections would start from national policy scenarios developed up through the year 2030 as modeled in GAINS. The resultant temporal policy feedback for the year 2030 would then reflect the implications of long-term mitigation strategies on short-term actions. While such an approach would provide a linkage between national energy-planning and global climate targets, additional effort is required to develop a set of adjusted MESSAGE baseline scenarios. Therefore, the hard-link of activity projections of both models was not employed for the analyses reported herein.

Besides their considerable environmental impacts, carbon mitigation policies might involve significant cost savings in air pollution control costs, because lower demand for fossil fuels will also reduce the need for installing air pollution control equipment.

In the standard GAINS approach mitigation costs are calculated for each country and each abatement measure at the production level as the difference to the costs of a reference situation. Thereby costs calculated by GAINS are additional expenditures needed to comply with current legislation or policies designed within the control strategy. This approach, however, cannot be applied directly to the MESSAGE activity projections because of different aggregation schemes. Instead, a set of **implied cost factors** can be derived from the GAINS scenarios until 2030. These cost factors define the average mitigation cost per unit of energy input in each aggregated MESSAGE sector for all abatement measures that are considered in GAINS. Cost factors for periods beyond 2030 have to be scaled proportionally to the change in the implied emission factors.

Obviously, this is a highly simplified approach to obtain cost-information on the co-benefits between air pollution abatement and climate mitigation. This approach also requires that the baseline projections for countries/regions under examination are not substantially different, otherwise the abated emission factors as well as the implied cost factors will not be representative enough to provide policy-relevant insights. Cost implications for the global emission scenarios, considering impacts of long-term climate strategies on the reduced cost for controlling air pollution, are not reported in this study, although a methodology for calculating cost factors has been reported for a linkage of GAINS with the POLES global energy model (Rafaj et al., 2009).

3 Air pollutant emissions of global long-term GHG scenarios

This section presents example calculations of long-term air pollutant emissions for two energy scenarios that result in different GHG concentration levels. Calculations employ a set of energy scenarios developed by IIASA's Greenhouse Gas Initiative (GGI) project which are summarized in Riahi et al. (2007). These scenarios accommodate a number of updates and revisions of the original scenarios reported in the IPCC Special Report on Emission Scenarios (IPCC, 2000). Information on the time evolution of the structure of the energy system and corresponding GHG emission levels can be retrieved directly from the online GGI scenario-database application (IIASA, 2007) accessible at http://www.iiasa.ac.at/web-apps/ggi/GgiDb.

3.1 Long-term activity projections

The update of the IIASA global emission scenarios comprises three baseline cases with different assumptions on socio-economic, demographic, and technological developments (for a summary of the storylines see Appendix II). The analysis presented in this paper employs the B2 scenario with medium greenhouse gas emissions compared to the A2 and B1 scenarios that illustrate possible upper and lower ranges of future emissions. Figure 4 compares the assumed economic growth in terms of per-capita-income for the B2 scenario.

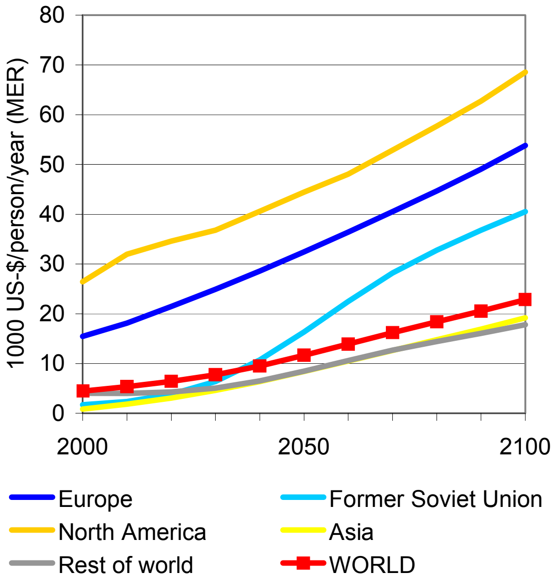


Figure 4: Income per capita by regions in the GGI B2 scenario. Adopted from IIASA (2007).

Combined with the assumed population growth, the economic development results in an increase of global GDP by a factor of 8 to 14 between 2000 and 2100 (Figure 5). It should be noted that the assumed GDP growth up to 2030 is lower than what was collectively assumed by national planners in 2007 as reported in Cofala et al. (2007a).

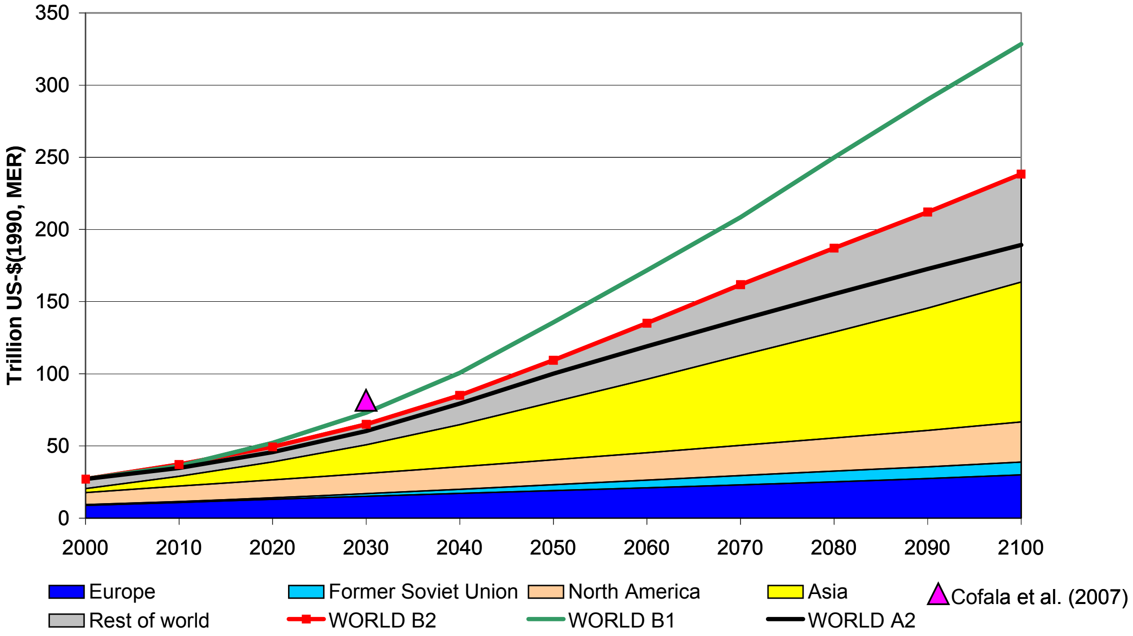


Figure 5: GDP growth by regions in the GGI B2 scenario. Adopted from IIASA (2007).

Global primary energy demand is assumed to increase by a factor of three compared to the year 2000 in the intermediate scenario B2 (Figure 6), although the other scenarios A2 and B1 indicate significant uncertainties in this field. In addition, composition of fuel consumption is rather different in the three cases (Riahi et al., 2007). While the "A2 world" relies heavily on fossil fuels and nuclear energy, the B2 and B1 cases show significantly larger use of biomass and non-biomass renewable energy sources. At the same time, natural gas serves as the 'transition fuel' to a post-fossil energy system. In the intermediate B2 scenario the largest share of coal consumption in the second half of the century will be used for combustion in the power sector and for the production of methanol, which is mainly used in the transport sector. Besides changes in the fuel mix, a massive shift towards cleaner technologies is assumed in the B2 storyline. Endogenous technological change is expected to dominate the emission reductions in the long term. For example, improved competitiveness of power supply options undergoing technological learning, such as IGCC plants or other clean coal technologies, will lead eventually to significant emission declines. In addition, the continuous reduction of energy intensity due to assumed economic restructuring and efficiency gains will imply significant decline in fuel use as well as in air pollutant emission.

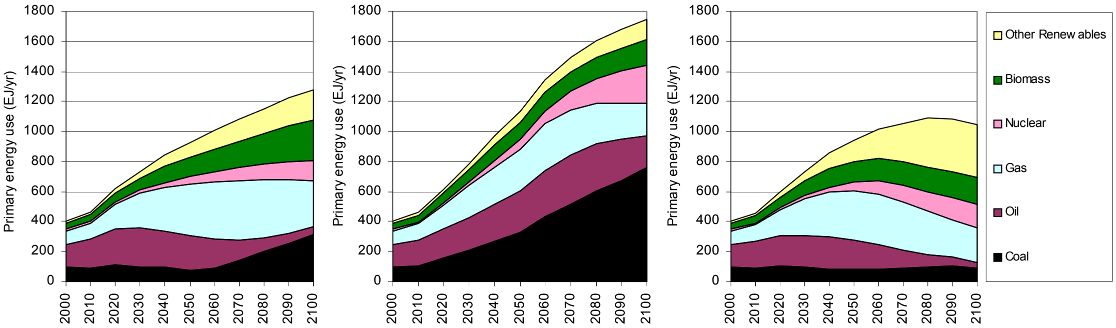


Figure 6: Global primary energy consumption by fuels in tree GGI baseline scenarios; from left to right B2, A2 and B1. Adopted from IIASA (2007).

While the B2 baseline scenario does not consider any explicit constraint on greenhouse gas emissions, analyses demonstrate that the volumes and composition of fuel consumption could change considerably with limitations on GHG emissions. Because of different mitigation potentials and costs, resulting cuts in GHG emissions differ largely across regions. Similarly, the underlying structural changes in the national and regional energy systems are strongly region-specific. However, in all scenarios decarbonization is achieved through lower consumption of fossil fuels due to higher use of zero-carbon energy sources (e.g., nuclear power and renewables) and energy efficiency improvements. The scenarios also provide estimates of other activity rates which are relevant for air pollution emissions, such as international shipping, enteric fermentation and manure management activities, rice cultivation and wastewater treatment (Rao and Riahi, 2006).

3.2 National legislation on air pollution control up to 2030

The calculations of air pollutant emissions presented in this paper employ an inventory of national emission control legislation as of 2009 that has been compiled for the GAINS model.

For the EU-27 it is assumed that (i) all emission control legislation as laid down in national laws will be fully implemented according to the foreseen schedule, (ii) that countries will comply with the EU National Emission Ceilings Directive, and (iii) that the Commission’s proposals on further emission control measures for heavy duty vehicles (EURO-VI, CEC, 2007a) and for stationary sources the revision of the IPPC Directive (CEC, 2007b) will be implemented.

For China, the set of emission control measures considers Chinese legislation as adopted in 2009 including (i) the use of high efficient electrostatic precipitators (ESP) at large combustion plants, (ii) increased use of low sulfur coal, (iii) increasing penetration of flue gas desulphurization (FGD) after 2005 in new and existing plants, (iv) adoption of EURO V standards for light and heavy duty cars after 2010, and (v) utilization of low sulfur fuels in vehicles from 2010 (Amann et al., 2008b).

For India, legislation includes requirements for (i) ESPs in the power and industrial sectors, (ii) primary measures for controlling NO_x emissions, and (iii) the state/city-specific implementation of Bharat Stages (equivalents of the EURO standards) for vehicular emissions (Amann et al., 2008c).

For North America (USA and Canada), the analysis includes the current national fuel quality and source-specific emission standards (Cofala et al., 2008).

For Latin America and other Asian countries, rapid progress in the introduction of stringent emission control standards for vehicles was assumed following the information summarized in ADB (2005) and DieselNet (2005). For Russia and other countries of the Former Soviet Union country-specific information, which was collected in the context of the revision of the Gothenburg protocol, has been used for stationary and mobile sources (Cofala et al., 2008b). Information for other countries is based on an update of the emission standards summarized in the emission standards handbook (McConville, 1997).

The temporal penetration of abatement measures in eight representative countries of the MESSAGE world regions for mobile and stationary sources is shown in Table 3 to Table 7.

Table 3: Implementation of different stages of EURO-standards for light-duty and heavy-duty vehicles.

COUNTRY	*2000*	*2005*	*2010*	*2015*	*2020*	*2025*	*2030*
EU	EURO-2/II	EURO-3/III	EURO-4/IV	EURO-5/V	EURO-6/VI	EURO-6/VI	EURO-6/VI
JAPAN	EURO-2/II	EURO-3/III	EURO-4/IV	EURO-5/V	EURO-6/VI	EURO-6/VI	EURO-6/VI
USA	EURO-2/II	EURO-3/III	EURO-4/IV	EURO-5/V	EURO-6/VI	EURO-6/VI	EURO-6/VI
RUSSIA		EURO-2/II	EURO-3/III	EURO-4/IV	EURO-4/IV	EURO-4/IV	EURO-4/IV
CHINA	EURO-1/I	EURO-2/II	EURO-3/III	EURO-4/IV	EURO-4/IV	EURO-4/IV	EURO-4/IV
INDIA	EURO-1/I	EURO-2/II	EURO-3/III	EURO-3/III	EURO-4/IV	EURO-4/IV	EURO-4/IV
BRAZIL	EURO-1/I	EURO-2/II	EURO-3/III	EURO-3/III	EURO-3/III	EURO-3/III	EURO-3/III
INDONESIA		EURO-2/II	EURO-2/II	EURO-2/II	EURO-2/II	EURO-2/II	EURO-2/II

Table 4: Fuel quality standards for maximal sulfur content in automotive fuels. Ppm is parts per million by volume.

COUNTRY	*2000*	*2005*	*2010*	*2015*	*2020*	*2025*	*2030*
EU	450 ppm	10 ppm	10 ppm	10 ppm	10 ppm	10 ppm	10 ppm
JAPAN	450 ppm	10 ppm	10 ppm	10 ppm	10 ppm	10 ppm	10 ppm
USA	450 ppm	450 ppm	10 ppm	10 ppm	10 ppm	10 ppm	10 ppm
RUSSIA	2000 ppm	450 ppm	450 ppm	450 ppm	450 ppm	450 ppm	450 ppm
CHINA	2000 ppm	2000 ppm	10 ppm	10 ppm	10 ppm	10 ppm	10 ppm
INDIA	2000 ppm	450 ppm	450 ppm	10 ppm	10 ppm	10 ppm	10 ppm
BRAZIL	450 ppm	450 ppm	450 ppm	450 ppm	10 ppm	10 ppm	10 ppm
INDONESIA							

Table 5: Projected use of measures to reduce NO_x emissions from stationary sources. CM is combustion modification. SCR is selective catalytic reduction.

COUNTRY	*2000*	*2005*	*2010*	*2015*	*2020*	*2025*	*2030*
EU	CM	CM/SCR	SCR	SCR	SCR	SCR	SCR
JAPAN	CM/SCR	CM/SCR	SCR	SCR	SCR	SCR	SCR
USA	CM	CM/SCR	CM/SCR	SCR	SCR	SCR	SCR
RUSSIA			CM	CM	CM	CM	CM
CHINA			CM	CM	CM	CM	CM
INDIA			CM	CM	CM	CM	CM
BRAZIL			CM	CM	CM	CM	CM
INDONESIA			CM	CM	CM	CM	CM

Table 6: Projected use of measures to reduce SO_2 emissions from stationary sources. FGD is flue gas desulphurization (full or partial adoption).

COUNTRY	2000	2005	2010	2015	2020	2025	2030
EU	FGD	FGD	FGD	FGD	FGD	FGD	FGD
JAPAN	FGD	FGD	FGD	FGD	FGD	FGD	FGD
USA	FGD-part	FGD-part	FGD	FGD	FGD	FGD	FGD
RUSSIA			FGD-part	FGD-part	FGD-part	FGD-part	FGD-part
CHINA	low S coal	low S coal	FGD-part	FGD-part	FGD-part	FGD-part	FGD-part
INDIA							
BRAZIL	FGD-part	FGD-part	FGD-part	FGD-part	FGD-part	FGD-part	FGD-part
INDONESIA	FGD-part	FGD-part	FGD-part	FGD-part	FGD-part	FGD-part	FGD-part

Table 7: Projected use of measures to reduce PM emissions from stationary sources. CYC is cyclone. ESP1 is Electrostatic precipitator: 1 field. ESP2 is Electrostatic precipitator: 2 fields. HED is high efficiency de-duster.

COUNTRY	2000	2005	2010	2015	2020	2025	2030
EU	ESP2	ESP2	HED	HED	HED	HED	HED
JAPAN	ESP2	HED	HED	HED	HED	HED	HED
USA	ESP1	ESP2	HED	HED	HED	HED	HED
RUSSIA	ESP1	ESP1	ESP1	ESP1	ESP2	ESP2	ESP2
CHINA	CYC	ESP1	ESP1	ESP1	ESP1	ESP2	ESP2
INDIA	CYC	ESP1	ESP1	ESP2	ESP2	ESP2	ESP2
BRAZIL	CYC	ESP1	ESP1	ESP1	ESP2	ESP2	ESP2
INDONESIA	CYC	ESP1	ESP1	ESP1	ESP1	ESP2	ESP2

3.3 Emission controls beyond 2030

Two alternative concepts for emission controls beyond 2030 have been identified in Section 2.3. In the first case, referred to as B2 CLE 2030, we assume no change of end-of-pipe emission control measures and their efficiencies beyond the status that will be reached in 2030. This case can also be described as the "CLE forever" scenario and defines an upper range of emission projections. The second approach postulates a further decline in emission intensities beyond 2030 based on the assumption that societies will opt for higher environmental quality with increasing welfare. It thus assumes that pollution legislation is further tightened beyond the CLE. For an approximation of the increasing stringency of pollution policies beyond 2030, and the associated improvements in technologies, we follow the concept of Environmental Kuznets Curves (EKC)[1].

There are number of empirical studies examining relations between wealth and pollution control. Stern and Common (2001) present a survey of long-term time series of global sulfur emission data and find that at the global scale SO_2 emissions per capita are a monotonic function of income, and reductions in emissions are time-related rather than income-related. They identify events, such as the adoption of the targeted control policies, as possible causes of

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[1] The EKC hypothesis suggests that there is an inverted U-shaped relationship, such that pollution first increases with the level of economic development and subsequently decreases, once a certain level of wealth has been passed. The relationship has been related to Kuznets, as the pattern found resembles the time path of income inequality relationship described by Kuznets (1955).

this time-dependency. In more recent study, which is based on the current emission evolution in China and other world regions, Stern (2006) concludes that, although air pollutants tend to increase with rising income, due to rapid technological change emissions decrease over time suggesting that a low income level does not prevent the adoption of abatement technologies. Other recent analyses suggest that in many developing countries controls of environmental quality are happening at faster rates than observed in the past in developed countries due to increased environmental awareness and technological diffusion (Dasgupta et al., 2001).

It can be expected that different levels of legislation, economic growth and technological progress across regions will cause different developments of emission intensities in the medium and long term (2030-2100). For this study, we assume that emission intensities improve as income levels progress according to the B2 CLE GDP projections. Income is thus used as a surrogate proxy for increasing environmental awareness within the B2 storyline. Following Smith et al. (2005) and Dasgupta et al. (2002), emission factors of technologies are assumed to decrease over time as income levels grow beyond levels of 5000-6000 $/capita. At the same time, the resulting emission coefficients are constrained in order not to decrease beyond those for the today's most efficient abatement measures.

3.4 Resulting emissions

Combining the short-term air pollution control policies as depicted in GAINS with the long-term evolution of the global energy system provided by MESSAGE allows for computing long-term trajectories for air pollutants such as SO_2, NO_x, CO, VOC, black carbon (BC) and organic carbon (OC). This chapter presents resulting long-term emissions and compares them trends obtained from short-term national projections and long-term scenarios. An illustration of the potential synergies between GHG mitigation and air pollution abatement for the baseline and climate-stabilization scenario is provided. Finally, emission projections for international shipping are reported.

3.4.1 The baseline scenarios

For the two concepts outlined above, SO_2, NO_x and CO emission projections for the B2 global energy scenario are compared with those of the SRES report (IPCC, 2000). The results from linked models are also compared to Cofala et al. (2009) and to an earlier study by Cofala et al. (2007a), which used the RAINS/GAINS model to develop two sets of global emission scenarios until 2030: a maximum feasible reduction (MFR) scenario and current legislation case (CLE). The energy projections in RAINS/GAINS originated mainly from national energy planning. In Cofala et al. (2009) the WEO scenarios (version 2009) have been implemented into the GAINS model in order to calculate the emission projections (WEO CLE) until 2030. In the examples provided below anthropogenic emissions from land-based sources (i.e., without international shipping and aircrafts) have been included in the comparison.

As can be seen in Figure 7, up to 2020 there is close agreement in the short-term trend projected for sulfur emissions for the B2 CLE 2030 and B2 CLE GDP cases calculated for this study and the CLE cases resulting from the WEO and RAINS assessments. Until 2020, the resulting trend closely correlates also with the SRES B2 baseline, although the projections differ significantly in absolute emission levels, which is attributed to the recalibration of the MESSAGE model during the development of the RCP scenarios mentioned in Section 1. After 2020, however, global SO_2 emissions in the B2 CLE 2030 and B2 CLE GDP scenarios are reduced at significantly higher rates in comparison to the SRES B2 case, mainly due to different assumptions on future emission control legislation. The figure also shows a large potential for further reduction in the case of full implementation of all SO_2 abatement options (i.e., the MFR case) until 2050.

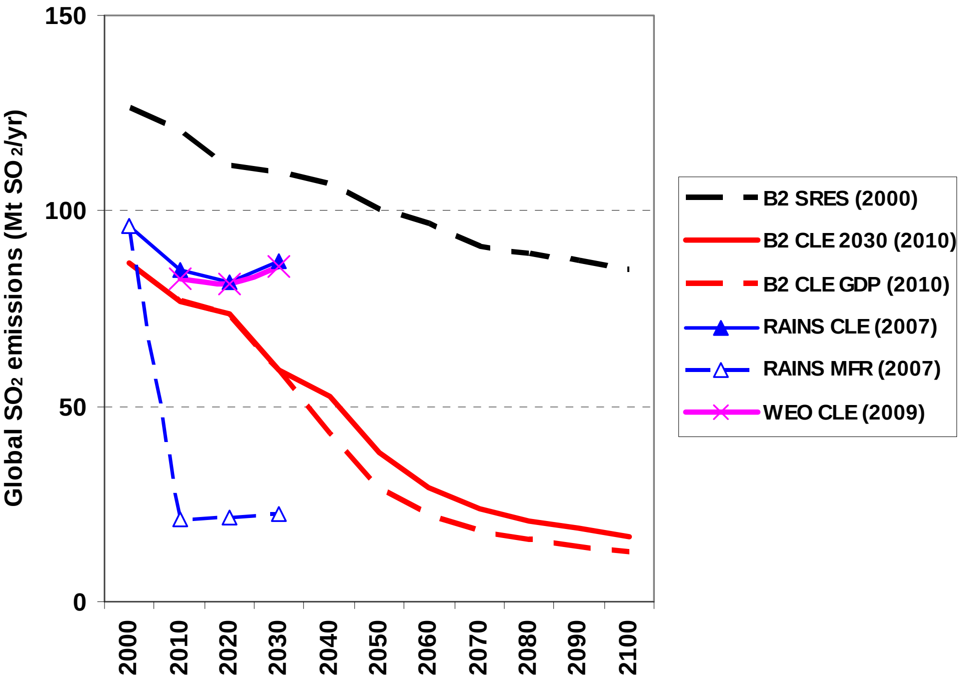

Figure 7: Comparison of global projections for SO_2 from anthropogenic land-based sources.

There is a difference of nearly 10 Mt SO_2 globally between the RAINS/GAINS and MESSAGE analyses in the period 2000 to 2020, which is explained by slightly different definition of sectors in the modeled energy systems, and by different calibrations of emissions for the base year (2000) in the MESSAGE model.

Trends in global NO_x emissions for the B2 CLE 2030 and the B2 CLE GDP cases (again from land-based sources) are also consistent with the RAINS CLE case and WEO CLE case until 2030. However, there is an absolute difference of about 10 Mt NO_x globally between these analyses in the year 2020, which is attributed mainly to differences in the underlying energy projections for the power sector and transport. However, Figure 8 reveals a large discrepancy in the NO_x emission trajectory between the original SRES estimates and the scenarios where current policies are adopted at the global scale. Towards the end of the century, the original SRES projection is four to five times higher than the scenarios which consider implementaotn of current emission control measures..

For global NO_x emissions, there is a significant difference between the scenario that assumes no strengthening of clean air policies beyond 2030 (B2 CLE 2030) and the B2 CLE GDP scenario where the pollution control stringency is assumed to follow changes in GDP per capita after 2030. As can be seen in Figure 8, NO_x emissions decline in both scenario variants towards 2100, however, total NO_x levels in B2 CLE GDP scenario is 50% lower than in the more conservative case represented by the B2 CLE 2030 scenario. The largest difference between these two cases occurs in the transport sector, where further improvements of vehicle fleet, fuel quality and penetration of catalytic converters beyond present legislation reduce emissions significantly below the CLE 2030 case.

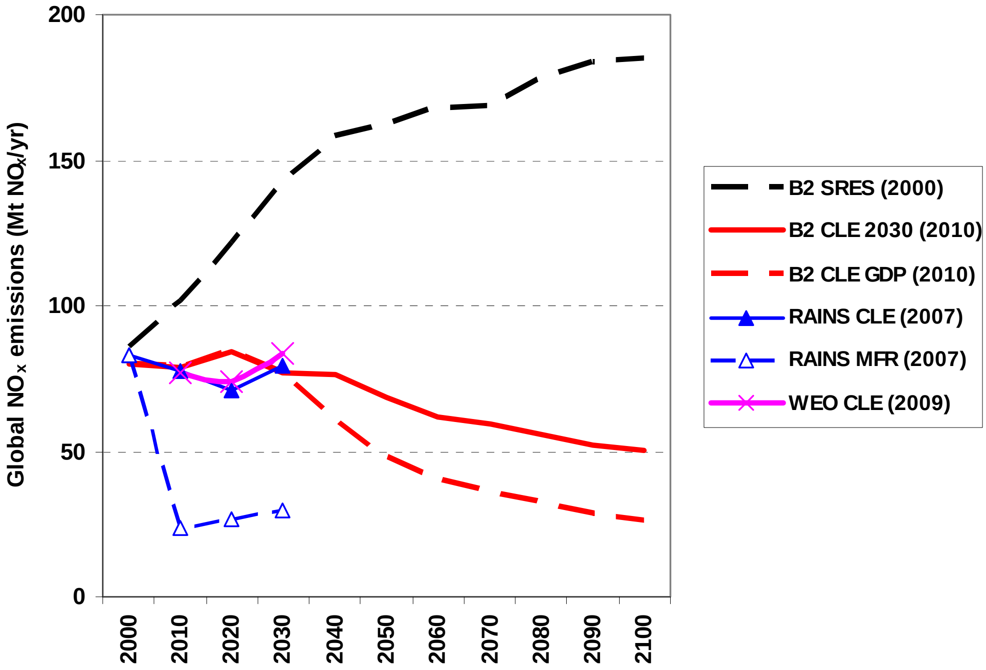

Figure 8: Comparison of global projections for NO_x from anthropogenic land-based sources.

For CO emissions from anthropogenic sources our calculations for the B2 scenarios project rather similar declining trends when compared with the RAINS CLE scenario for 2000-2030. In contrast, CO emissions increase in the SRES B2 scenario because current emission control legislation has been ignored in this scenario. In addition, Figure 9 suggests that adoption of the full portfolio of technological options (i.e., the RAINS MFR case) could eventually lead to further CO reductions than what is implied with current legislation. For all three pollutants under examination, the reason for the differences in the projected emission levels around the year 2020 are different assumption on fuel consumptions between national planners, the WEO and the B2 CLE scenario.

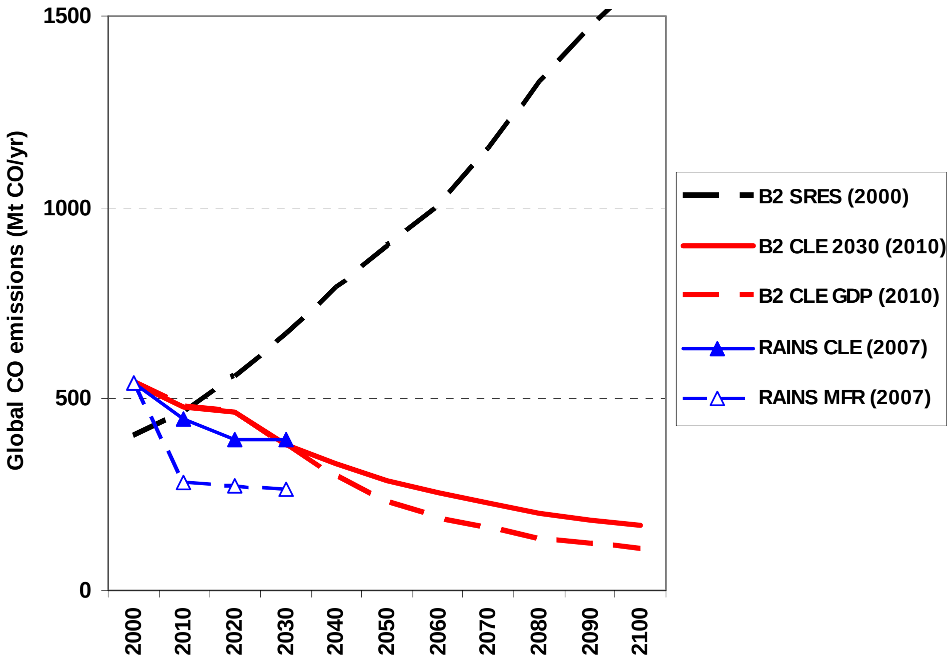

Figure 9: Comparison of global projections for CO emissions from anthropogenic land-based sources.

3.4.2 Air pollution emissions in GHG stabilization scenarios

In addition to their positive impacts on climate change, greenhouse gas mitigation strategies result in numerous positive side effects in other policy areas, such as reduced environmental pressure or improved energy supply security (Amann et al., 2008d). As discussed in Section 3.1, policies targeted at global GHG stabilization require significant changes in the global energy system. The methodology presented in this report allows quantifying the co-benefits of such changes on emissions of air pollutants. It should be emphasized that the synergies of GHG mitigation emerge solely from the reconfiguration of the energy system, and not from more stringent air pollution emission control measures under a climate protection regime.

The relation between CO_2 mitigation and air pollution abatement is depicted in Figure 10, showing the reductions in land-based SO_2, NO_x and CO emissions relative to the CO_2 reductions that emerge from decarbonization targets. Such targets force global GHG concentrations to stay below 450 ppm CO_2 equivalents within the computation period 2000-2100. The figure shows that until 2030 the 30% CO_2 reduction compared to the baseline is accompanied with nearly proportional reductions of SO_2 and NO_x emissions. However, until 2050, these co-benefits decrease in relative terms, as the air pollution reduction potential will be largely exploited already in the CLE cases without climate constraints. In addition, the B2 baseline energy scenario assumes a high share of clean and zero-carbon fuels in the fuel-mix, which leaves only a limited space for further fuel substitution in the mid of the century. Reductions in CO in the climate mitigation case, while being significant, are not as high as for SO_2 and NO_x due to the high effectiveness of CLE measures within the transport sector and because of continued solid fuel combustion in the households, even if fuel switches are taken into account. Figure 8 also illustrates the range of co-benefits originating from different assumptions on the implementation schedules of pollution controls between the conservative scenario with fixed emission coefficients (B2 CLE 2030) and the more optimistic case assuming faster implementation of abatement measures globally due to growing welfare (B2 CLE GDP).

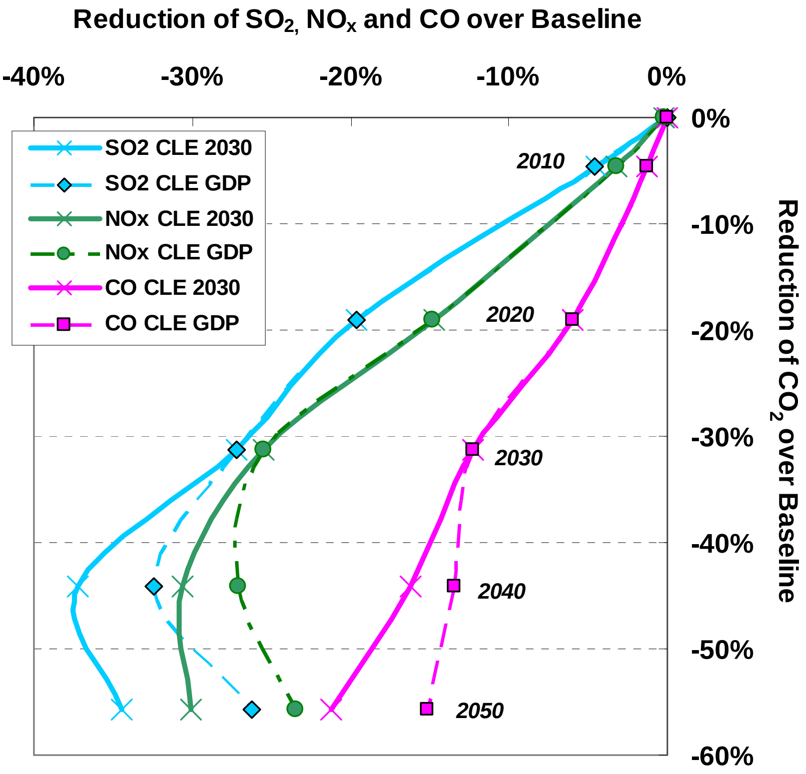

Figure 10: Reduction of global air pollution relative to the CO_2 emission reductions in the climate stabilization scenario (B2_450ppm) over the B2 baseline.

4 Projections of future emissions from marine shipping

For developing consistent global long-term emission trajectories it is important that all important emission sources are taken into account. Although the international shipping sector is not explicitly represented in either the GAINS or the MESSAGE modeling frameworks, it is expected to contribute significantly to emissions in the next few decades. This section explains the methodology for calculating future emissions from this sector using the underlying GDP and energy projections of the MESSAGE scenario.

With growing GDP, trade volumes and thus ship movements are expected to substantially increase in the future, which will lead to higher fuel consumption and combustion exhausts from this activity. Emissions from international ships are not subject to national regulations, but are dealt with by agreements under the Marine Pollution Convention (MARPOL) of the International Maritime Organization (IMO, 1998).

The projections of NO_x emissions from international ships reported here are based on the methodology described in Eyring et al. (2005) and reflect the implementation of the recent IMO standards (IMO, 2008) under the “current legislation” policy scenario overlaying the B2 reference case. Future fuel consumption by international ships is derived from historical relations between GDP, seaborne trade and the number of ships. Figure 11 shows the time evolution of global GDP in the B2 scenario and the corresponding fuel use in ship engines. An important assumption concerning the future exhausts from ships is related to the expected efficiency improvements and the use of alternative fuels. Three cases are illustrated for efficiency improvement ranging from 0% to 25%. The latter case corresponds most closely to the storyline of the B2 scenario, which implies a significant technological learning and innovation processes.

It is further assumed that all new ships will comply with the IMO standards. Eyring et al. (2005) indicates that the original IMO compliance would reduce in 2050 average NO_x emission factors for shipping by 30% relative to present day (IMO old), while the updated IMO standards reduce specific emissions by 70% (IMO new). The actual emission reduction due to the adoption of the IMO regulations itself is a source of uncertainty. For instance, Cofala et al. (2007b) suggests a lower reduction impact due to IMO standards for NO_x at around 15%.

To illustrate the combined impact of the assumptions on efficiency improvements and lower emission factors, a set of sensitivity cases is presented in Figure 11 (right panel). In 2100 ship emissions could range between more than 65 Mt NO_x (without any emission controls) and 4 Mt when assuming 25% fuel savings and NO_x control measures beyond the recent IMO requirements (IMO new+). In the less optimistic scenario (i.e., efficiency improvements of 10% and the 15% lower emission rates) the increase in global NO_x shipping emissions would compensate the emission reductions achieved at the land-based emissions.

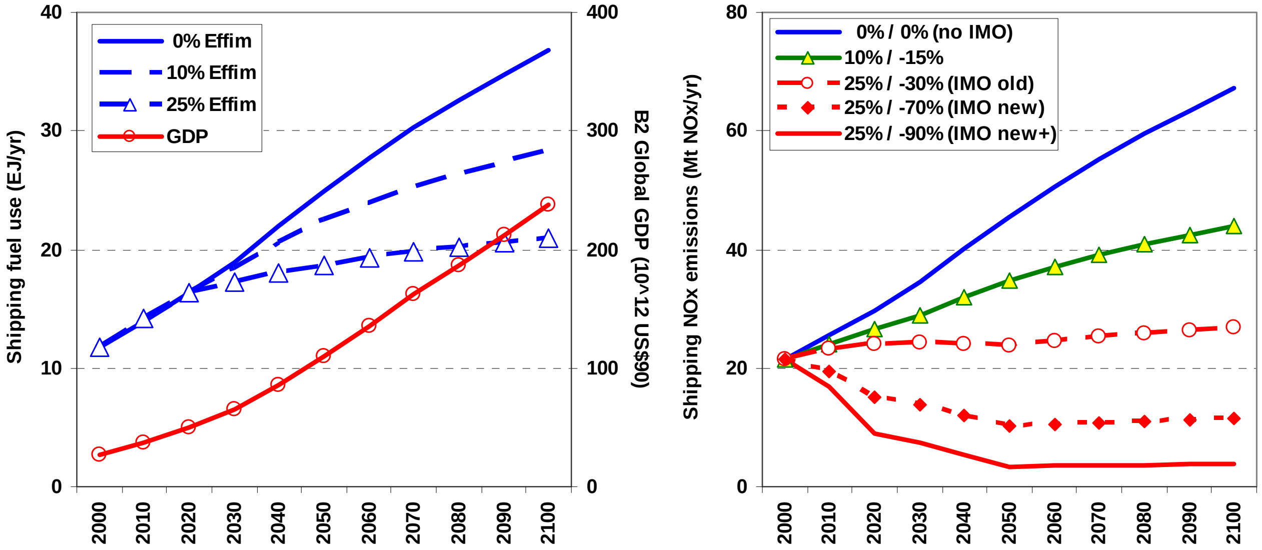

Figure 11: Global GDP in the B2 scenario and global fuel consumption for international shipping assuming different level of efficiency improvements (Left panel). Global NO_x emissions from international shipping; the first column in the legend refers to the efficiency improvement assumed; the second column refers to the expected decrease in the average emission factor by 2050 (Right panel).

5 Conclusions

In order to quantify co-benefits of GHG abatement for air pollution, it is necessary to combine existing information on short-term emission control legislation in the various world regions with long-term projections of energy use. This report presents a methodology to link short- and long-term energy scenarios and calculate resulting air pollution emissions in a coherent way. The methodology has been implemented for the GAINS and MESSAGE models developed at IIASA. While this approach enables an outlook into longer term perspectives of air pollution emissions, the usual uncertainties associated with projecting the distant future prevail. These include uncertainties about economic development, population growth, technology dynamics, and the extent and speed of implementation of specific air quality policies.

To illustrate the impact of such uncertainties, the paper presents two cases with different assumptions on future air quality legislation: a) a pessimistic case assuming that technologies and legislation would not change beyond 2030, and b) a more optimistic case where emission standards in all countries continue to improve and converge over time to today’s best available technology. These two cases result in significantly different emission levels, especially for NO_x. The difference in the results illustrates clearly the importance of transparent reporting of underlying assumptions for air quality policies in long-term greenhouse-gas emission scenarios. Similarly, the interpretation of the results requires careful consideration. For instance, air pollutant emissions from scenarios that assume technological improvements in emission factors should not be misinterpreted as autonomous trends in absence of dedicated air pollution policies. This would discount the need for future air quality legislation, while in fact in the past much of the improvements in air pollution emissions resulted from targeted policy interventions. By the same token, long-term energy scenarios that assume no further technological improvements are likely to overestimate future air pollution emissions, as policy interventions could be quite successful in reducing emission levels, as has been demonstrated in the past.

The report also highlights a few methodological issues. First, the underlying baseline activity projections scenarios developed with the MESSAGE model and the national/regional scenarios implemented in GAINS should be in reasonable agreement, so that the emission factors that serve as model interface are representative for the given scenario. Furthermore, emission characteristics of future technologies have to be assessed carefully. New technologies, many of them not existing at present, are expected to dominate the energy markets in the second half of century and will determine future emission profiles. The levels of emissions reductions and associated costs of the implementation of current legislation will depend strongly on the level of the emissions in the reference scenario, as well as on the choice of the baseline assumptions with respect to technology and structural changes in the energy system.

For the next few decades the trends of SO_2, NO_x and CO emissions in the global B2 CLE scenarios agree well with the short-term "current legislation" scenarios that rely on national energy projections. However, the new global long-term emission projections, especially for NO_x and CO, are significantly lower than those reported earlier, for example in the SRES/IPCC scenarios, as these earlier scenarios did not foresee the recent air pollution control in many parts of the world.

International shipping will constitute an increasing source of global air pollution emissions. A parametric analysis of NO_x emissions from international maritime shipping shows that the benefits of all efforts to reduce land-based emissions could be leveled out by a 2% annual growth in global maritime shipping emissions, unless the recent IMO standards were effectively implemented.

The paper also indicates that the implementation of stringent carbon mitigation strategies will also lead to significant reductions in air pollution emissions due to changes in the fuel mixes and demand reductions. Especially the rapid substitution of coal with low carbon fuels in the power sector will reduce SO_2 and NO_x emissions as a side effect.

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Appendix I

Query statement routine to calculate abated emission factors from the GAINS database compatible with the energy system of the MESSAGE model (example for NO_x emissions).

```
URL:jdbc:oracle:thin:@seine.iiasa.ac.at:1521:RESRCH2
-------------------------------------------------------------------------
-------------------------------------------------------------------------
delete from gains_glob.emiss_tmp

insert into gains_glob.emiss_tmp  select r.m_reg, r.idregions, r.country,
e.IDPOLLUTANT_FRACTIONS,
  e.idyears, e.idact, e.idsec, e.activity, e.emiss  from
gains_glob.MESSAGE_REGIONS_ALL r join rains_europe.emiss_all_message e
  on r.idregions=e.idregions and r.gains_scen=e.idscenarios  where
r.gains_scheama='rains_europe'  and IDPOLLUTANT_FRACTIONS in('NOX')
-- rains_europe-->17303

insert into gains_glob.emiss_tmp  select r.m_reg, r.idregions, r.country,
e.IDPOLLUTANT_FRACTIONS,
  e.idyears, e.idact, e.idsec, e.activity, e.emiss  from
gains_glob.MESSAGE_REGIONS_ALL r join gains_china.emiss_all_message e
  on r.idregions=e.idregions and r.gains_scen=e.idscenarios  where
r.gains_scheama='gains_china'  and IDPOLLUTANT_FRACTIONS in('NOX')
-- gains_china-->15160

insert into gains_glob.emiss_tmp  select r.m_reg, r.idregions, r.country,
e.IDPOLLUTANT_FRACTIONS,
  e.idyears, e.idact, e.idsec, e.activity, e.emiss  from
gains_glob.MESSAGE_REGIONS_ALL r join gains_india.emiss_all_message e
  on r.idregions=e.idregions and r.gains_scen=e.idscenarios  where
r.gains_scheama='gains_india'  and IDPOLLUTANT_FRACTIONS in('NOX')
-- gains_india-->9849

insert into gains_glob.emiss_tmp  select r.m_reg, r.idregions, r.country,
e.IDPOLLUTANT_FRACTIONS,
  e.idyears, e.idact, e.idsec, e.activity, e.emiss  from
gains_glob.MESSAGE_REGIONS_ALL r join gains_world.emiss_all_message e
  on r.idregions=e.idregions and r.gains_scen=e.idscenarios  where
r.gains_scheama='gains_world'  and IDPOLLUTANT_FRACTIONS in('NOX')
-- gains_world-->16102

select e.idyears, r.m_reg, e.IDPOLLUTANT_FRACTIONS as pollutant,  t1.sec_message as
tec,
   sum(e.ACTIVITY) as activity, sum(e.emiss) as emiss, sum(e.emiss)/sum(e.ACTIVITY) as
ief
  from gains_glob.emiss_tmp e  join gains_glob.message_regions_all r on
r.idregions=e.idregions
  inner join gains_glob.trans_message_all t1 on t1.idact=e.idact and t1.idsec=e.idsec
where e.IDPOLLUTANT_FRACTIONS in('NOX')
  group by e.idyears, r.m_reg, e.IDPOLLUTANT_FRACTIONS,  t1.sec_message
  order by e.IDPOLLUTANT_FRACTIONS, r.m_reg, t1.sec_message,  e.idyears

select e.idyears, r.m_reg, e.IDPOLLUTANT_FRACTIONS as pollutant,  t1.sec_message as
tec, e.idsec, e.idact,
   sum(e.ACTIVITY) as activity, sum(e.emiss) as emiss, sum(e.emiss)/sum(e.ACTIVITY) as
ief
  from   gains_glob.emiss_tmp   e     join   gains_glob.message_regions_all   r   on
r.idregions=e.idregions
  inner join gains_glob.trans_message_all t1 on t1.idact=e.idact and t1.idsec=e.idsec
where e.IDPOLLUTANT_FRACTIONS in('NOX')
  group  by  e.idyears,  r.m_reg,  e.IDPOLLUTANT_FRACTIONS,  t1.sec_message,  e.idsec,
e.idact
  order  by  e.IDPOLLUTANT_FRACTIONS,  r.m_reg,  t1.sec_message,  e.idsec,  e.idact,
e.idyears



-------------------------------------------------------------------------
```

Appendix II

Characteristics of global GGI scenarios, derived from Riahi et al. (2007).

Scenario	Description
B2	This scenario anticipates a world in which the emphasis is placed on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing population at a moderate rate, intermediate levels of economic development, and a diverse technological change. The B2 scenario is characterized by 'dynamics as usual' rates of change, inspired by historical analogies where appropriate. World population growth is assumed to reach some 10 billion by 2100, assuming strong convergence in fertility levels toward replacement levels, ultimately yielding a stabilization of world population levels. The economic growth outlook in B2 is regionally more heterogeneous, with per capita income growth and convergence assumed to be intermediary between the two more extreme scenarios A2 and B1. Global economic output increases by a factor of 10 until 2100. Global carbon emissions rise initially along historical rates (to some 13 Gt by 2050), but growth would eventually slow down (14 Gt by 2100) as progressively more regions shift away from their reliance on fossil fuels, a twin result of technological progress in alternatives and increasing scarcity of easy-access fossil resources.
A2	The A2 storyline describes a very heterogeneous world with a slow convergence of fertility patterns across regions. The resulting 'high population growth' scenario adopted here is expects 12 billion by 2100. Economic development is primarily regionally oriented and per capita economic growth and technological change is more fragmented and slower than in other scenarios. In this scenario, per capita income growth is the lowest among the scenarios explored and converges only extremely slowly, both internationally and regionally. The more limited rates of technological change that result from the slower rates of both productivity and economic growth translates into lower improvements in resource efficiency across all sectors. Energy supply is increasingly focused on low grade, regionally available resources (i.e., primarily coal), with post-fossil technologies (e.g., nuclear) only introduced in regions poorly endowed with resources. The resulting energy use and emissions are consequently highest among the scenarios with carbon emissions that approach 20 Gt by 2050 and close to 30 Gt by 2100 (compared to 8 Gt in 2000).
B1	The B1 storyline describes a convergent world with a low global population growth that peaks in mid-century and declines thereafter to some 7 billion by 2100, but with rapid changes in economic structures towards a service and information economy, with reduction 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. It is assumed that per capita GDP growth is the highest of the scenarios analyzed. Also, incomes are assumed to converge both internationally and domestically. Combined with the assumed global availability of clean and high-efficiency production technologies for food, raw materials, energy, and manufacturing, differences in resource and environmental productivities are reduced significantly, which leads to comparatively low levels of GHG emissions even in the absence of dedicated climate policies. Carbon emissions, for instance, peak at some 10 Gt by 2050 to fall below current levels thereafter (5 Gt by 2100), with the progressive international diffusion of rapidly improving post-fossil technologies.