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The Triptych approach revisited

A staged sectoral approach for climate mitigation

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Rapport in het kort

De verbeterde Triptiek benadering

Een stadium, sectorale benadering voor toekomstige mitigatie verplichtingen

De Triptiek-benadering is een methode voor differentiatie van toekomstige verplichtingen tussen landen gebaseerd op technologische criteria op sectoraal niveau. De emissie-reductiedoelstellingen worden opgedeeld over de verschillende sectoren, waardoor het mogelijk is om dit te koppelen aan werkelijke reductiestrategieën. De nieuwe *Triptiek 7.0* die hier wordt gepresenteerd is een verbetering ten opzichte van eerdere versies, vooral doordat het meer transparant is en het een vertraagde deelname toelaat voor de ontwikkelingslanden (initiële deelname van de ontwikkelingslanden met een stimulans door ‘no lose’ doelstellingen of duurzame ontwikkeling beleidsmaatregelen). Dit rapport presenteert de emissie reductiedoelstellingen van 224 landen voor drie scenario’s die broeikasgasconcentratie stabiliseren op 450, 550 en 650 ppm CO_2-eq.. De reducties zijn ambitieus, maar verenigbaar met bestaande technische reductiepotentiëlen.

Trefwoorden: Post-2012 regimes, sectorale doelstellingen, UNFCCC, toekomstige verplichtingen, technologie, emissies, klimaatveranderingen, broeikasgassen

Contents

Summary

How can an international agreement on climate change distribute responsibilities and emission reduction requirements between countries to be effective, technically feasible and is viewed as fair? This report further develops the Triptych approach as one possible answer to this question.

The Triptych approach defines the criteria and rules for differentiating future commitments for all countries in a consistent and transparent manner. The advantage of the Triptych approach is that the rules to distribute emission allowances are different for each sector and are thereby linked to real-world emission reduction strategies. Its framework also allows for discussions on sectors that compete worldwide and, in a natural manner, on the role of developing countries in making contributions to emission limitation and reduction targets. The major downside of the approach, however, remains its complexity and the necessity for projections of production growth rates.

The Differentiated Convergence Triptych 7.0 presented in this report builds on an earlier version of the Triptych approach by refining the methodology to improve the transparency of the approach (e.g. a simplified methodology for the electricity sector) and to accommodate the tendency of developing countries to act only after industrialized countries have acted (initial participation of developing countries with incentives but no penalties through ‘no-lose’ targets or sustainable development policies and measures).

The approach has been implemented using a policy decision-support tool, the FAIR model, and the implications of the approach on the emission allowances of 224 countries are presented for the three sets of Triptych parameters – the slow, medium and strong scenario, respectively. The strong scenario is compatible with a stabilization of greenhouse gases (GHGs) at 450 ppm CO_2-eq., and the medium scenario with a stabilization of GHGs at 550 ppm CO_2-eq. All three scenarios show that significant emission reductions are required for all regions. The reductions may sound very ambitious and (at first sight) politically unacceptable, but this study also shows that these are achievable in the short term with currently available technology and in the long term with very likely available technological options.

The modelling also clearly demonstrates that the very different emission profiles of countries can be considered in both an explicit and differentiated manner using the Triptych approach. The emission profiles of Brazil (dominated by agriculture) and China (dominated by use of coal) lead to different reduction requirements, because the Triptych methodology applies different rules for the different sectors.

We believe that even if the Triptych approach is not used as an officially recognized tool in its entirety during future negotiations, its elements constitute a useful input into such discussions and may eventually find an application in a definitive international climate agreement.

1 Introduction

The focus of attention in international climate negotiations has shifted from design of the specific rules of the first commitment period of the Kyoto Protocol (2008-2012) to strengthening the international framework for the years following the Kyoto Protocol's initial commitment period. At the eleventh Conference of the Parties (COP-11) in Montreal, December 2005, countries agreed to start discussing the next steps to be taken, both under the Kyoto Protocol and under the United Nations Framework Convention on Climate Change (UNFCCC; see www.unfccc.int).

The long-term objective of the UNFCC (UNFCCC, 1992) is to stabilize the atmospheric greenhouse gas (GHG) concentration at a level that would avoid dangerous climate change impacts (Article 2). Consequently, the overriding challenge is to design an agreement that includes all of the major emitting countries – both developed and developing – and to commence on taking the necessary steps to achieve significant long-term reductions of global emissions. To this end, many proposals for differentiating commitments among countries have been developed, including those developed by Parties to the UNFCCC as well as others published in the literature (see Aldy et al., 2003; Blok et al., 2005; Bodansky, 2004; Kameyama, 2004; Torvanger and Godal, 2004 for an overview).

In this study, the global Triptych approach is developed further as a tool for allocating future emission allowances amongst countries within the framework of the international decision-making process on the differentiation of post-2012 commitments. The Triptych approach attempts to incorporate a number of widely supported notions in the climate debate, the most important of which are the necessity for technological improvement, the transition to low emissions and the desirability of reduction differences in per capita emissions. The Triptych approach assigns emission reduction commitments to individual countries according to common rules using country-specific sector and technology information. These common rules allow for growth in economic activities (more for developing countries and less for developed countries) and require an improvement in efficiency or emission intensity. Although the Triptych approach is more sophisticated and, consequently, more data intensive than a number of other approaches (for example, those based on converging per capita emissions), these attributes provide it with the capability to take the diverse national circumstances of countries better into account.

The Triptych approach was originally developed at the University of Utrecht and has been used for supporting decision-making when differentiating the European Union's (EU) internal Kyoto target among its Member States both before and after Kyoto (COP-3) (Blok et al., 1997; Phylipsen et al., 1998; Ringius, 1999). It may, therefore, serve the same purpose on a much broader international level.

The *Original Triptych* approach only comprised energy-related CO_2 emissions and highlighted three sectors: (1) internationally orientated, energy-intensive sectors of industry (or heavy industry),[1] (2) the domestic sector[2] and (3) the electricity power sector. The initial selection of these categories was based on a number of differences in national and sectoral circumstances that were considered in the negotiations to be relevant to emission reduction potentials: differences in economic structure and the competitiveness of internationally oriented industries, in the standard of living and in the fuel mix for the generation of electricity. The emissions of the three categories are treated differently in that for each of the categories a reasonable emission allowance is calculated while at the same time relevant national and sectoral circumstances are taken into consideration. The methodology derives these allowances for each sector using uniform rules applied equally to all countries, and the sum of the emissions allowances of the categories is the national allowance for each country. Only one national target per country is proposed – no sectoral targets – in order that countries be given more flexibility to pursue cost-effective emission reduction strategies.

In the years following the development of the Original Triptych, the approach was extended to the global scale and to include more sectors as well as non-CO_2 GHGs (methane, CH_4; nitrous oxide, N_2O; hydro fluorocarbons, HFCs; per fluorocarbons, PFCs; sulphur hexafluoride, SF_6).[3] The Global Convergence Triptych developed by Groenenberg et al. (2004) includes a target-oriented calculation scheme for calculating emission allowances from six sectors – fossil fuel production, agriculture and deforestation as well as the original three energy-using sectors – in which both CO_2 and non-CO_2 emissions are taken into account at the level of world regions. The scheme defines global long-term sustainability targets for the GHG intensity of electricity production, for energy efficiency in the energy-intensive industry and for per capita emissions in the domestic sectors. Bottom-up data on sectoral reduction opportunities are used to set the level of the sustainability targets. The Global Convergence Triptych approach allows for a certain growth in activity in the various sectors and considers advanced technological opportunities to minimize their emissions. The level of growth activity allowed is based on medium growth projections for the various sectors. This Triptych approach has been used to review differentiation commitments for the 2010–2050 time frame.

A logical next step was to extend the calculation of the emission allowances to the level of countries, as individual countries are the actors in international negotiations and the emission profiles of countries may be very different even within one geographic region – for example, South Korea and China. Hence, individual countries are interested in the implications of various approaches for determining their emission levels. The Triptych 6.0 approach (Höhne et al., 2005) was the first attempt to extend the calculations to individual countries, and it

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[1] Iron and steel, chemicals, pulp and paper, non-metallic minerals, non-ferrous metals and the energy transformation sector, including petroleum refining, the manufacture of solid fuels, coal mining, oil and gas extraction and any energy transformation other than electricity production.

[2] The domestic sectors comprise various sectors: not only the residential sector (households), but also the commercial sector, transportation, and light industry are included in this category, as are CO_2 emissions related to combustion in agriculture and during the production of fossil fuels.

[3] Appendix A compares the main differences and similarities of the earlier Triptych methodologies.

incorporates two new elements in the methodology compared to the Global Convergence Triptych approach:

1. updated growth rates for the electricity and industrial production sectors combined with a ‘normative but scenario-derived’ approach or, stated otherwise, countries with low per capita income are allowed higher growth rates than in the default scenario, while countries with high per capita income are allowed lower growth rates than in the default scenario;
2. for the power sector, the emissions are based on assumptions for future shares of nuclear power and renewables and for changes in the fuel mix in fossil fuel-based power plants as well as for convergence in fossil fuel-based power generation efficiencies.

Furthermore, for the growth in the industrial production, Höhne et al. (2005) introduced a uniform ‘structural change factor’. This was a necessary adaptation since countries’ future industrial productivity data for the default scenario that accounts for structural changes were not available and, consequently, the economic indicator ‘industrial value added’ had to be used for future industrial productivity levels – and this indicator usually increases much faster than physical industrial production. The structural change factor converts the total ‘industrial value added’ into physical production growth of heavy industry. It therefore has a significant influence on the results for the industry sector.

The methodology of the updated Triptych approach (‘Differentiated Convergence Triptych 7.0’, hereafter simply Triptych 7.0) presented in this study includes several other new elements that were added in response to the shortcomings of earlier implementations of the Triptych approaches:

- The calculation of the future emissions in the power sector assumes a *growth in electricity consumption*, an annual *electricity consumption efficiency* improvement (a decrease in demand), *convergence of generation efficiencies per fuel and a decrease of the coal and oil shares* in the electricity mix (for more details, see section 2.5). This methodology simplifies the calculation of emissions from the electricity sector compared to earlier versions and also solves some of the problems encountered using *Triptych 6.0*, such as the consideration of Combined Heat Power (CHP) or the implementation of shares of renewable and nuclear energy sources per country. The new methodology avoids the detailed estimation of efficiency improvements and conversion factors, and it leaves more freedom to countries in terms of how they would like to fulfil their share – with CO_2-free energy by renewables, nuclear energy and CO_2 capture and storage (CCS), or with low-CO_2 energy (natural gas)
- ‘Common but differentiated responsibilities’ convergence, which means that all convergence trajectories in the methodology are based on a ‘common convergence’, but are ‘differentiated’ in time. This translates into developing countries having the same obligation as developed countries to reduce emissions, but the obligation is delayed and conditional to the actions carried out by developed countries. This concept is based on the idea of Höhne et al. (2006a). Delayed participation of (least) developing countries

could overcome data implementation problems for these countries (for more details, see section 2.2).

- Prior to participating in the convergence trajectories, developing countries commit in a clear and definite manner by adopting sustainable development objectives, the so-called *Sustainable development policies and measures (SD-PAMs)* or *no-lose targets*. For the implementation in the model, a uniform percentage reduction from baseline emissions for all sectors is assumed. The countries can decide whether they want to achieve this reduction with SD-PAMs or no-lose targets (for more details, see section 2.2).

The model implementation of the Triptych 7.0 approach in this report includes several other improvements compared to the earlier Triptych 6.0 version:

- The growth of industrial production is based on *total final energy consumption in industry* taken from the recently updated IMAGE 2.3 implementation of the International Panel on Climate Control Special Report on Emissions Scenarios (Nakicenovic et al., 2000) (hereafter IMAGE 2.3 IPCC-SRES scenarios) (Van Vuuren et al., 2006a). As such, it also better accounts for structural changes in the industrial sector as well as autonomous baseline energy efficiency improvements compared to the earlier used growth in monetary value as “industrial value added” (for more details, see section 2.3 and Van Vuuren et al. (2006b)). This method is simpler and more coherent than that used in Triptych 6.0.
- Energy efficiency indices are based on *national specific data*, which are estimated in *Triptych 7.0* for all individual countries based on the work of Kuramochi (2006) (for more details, see section 2.3). These indices are based on recent statistics data as compared to older and regional data applied at the level of countries used in Triptych 6.0 for the energy efficiency indices (from Groenenberg (2002)).
- This report uses an updated baseline scenario of population, gross domestic product (GDP) and emissions at the level of 224 individual UN countries. This baseline scenario was derived from a downscaling methodology, based on the work of Van Vuuren et al. (2007), applied on the updated IMAGE 2.3 IPCC-SRES scenarios (Van Vuuren et al., 2006a) (for details, see section 2.1).[4]
- The historical datasets of CO_2 emissions at the level of all sectors has been updated with the most recent estimates of the International Energy Agency (IEA, (2005a) and EDGAR datasets (Olivier et al., 2005) to 2003. The base-year for all other data, such as other GHGs, population, GDP, among others, remains 2000 (for more details, see section 2.1).

Note that both the renewed approach and Triptych 6.0 use the same definition of *emission allowances*, which is CO_2-equivalent emissions, including the anthropogenic emissions of six

[4] Under *Triptych 6.0*, a set of baseline scenarios for population, GDP and sectoral emissions at the level of countries, based on a linear downscaling method for the IMAGE 2.2 IPCC-SRES emission scenarios (Nakicenovic et al., 2000) was used. This methodology was highly criticized in the literature (see Den Elzen, 2005; Pitcher, 2004; Van Vuuren et al., 2007), as it may lead to unrealistic results.

Kyoto GHGs (fossil CO_2, CH_4, N_2O, HFCs, PFCs and SF_6 (using the 100-year GWPs of IPCC, 2001)) but excluding LULUCF (land-use and land-use change and forestry)-related CO_2 emissions.[5]

This report is structured as follows. Chapter 2 describes the methodology of the updated Triptych approach, as implemented in our modelling framework, FAIR 2.1, at the level of individual countries (Den Elzen, 2005; Den Elzen and Lucas, 2005). Chapter 3 presents the emission allowances for three scenarios, including different convergence trajectories, and analyses whether these are compatible with achieving long-term GHG concentrations targets. Chapter 4 discusses the advantages and disadvantages of the Triptych approach and presents the main conclusions of this report.

[5] Emissions from LULUCF sources are highly uncertain, and emission estimates from various sources are often not consistent. Therefore, it has also been suggested to treat emissions from deforestation with a different instrument separate from other emissions (WBGU, 2003).

2 Description of the Differentiated Convergence Triptych 7.0 approach

This chapter describes the Triptych 7.0 approach in more detail. Table 1 presents an overview of the approach, the data requirements and the exogenous parameters that have to be chosen. Section 2.1 describes the modelling tool used for calculating countries' emission allowances in the Triptych 7.0 approach. Section 2.2 describes the major new element of the Triptych 7.0 approach, the differentiated participation. Sections 2.3 to 2.7 describe the methodologies applied for the seven Triptych sectors – industry, electric power generation, domestic sector, non-combustion emissions from fossil fuel production, agriculture, waste and land-use CO_2 emissions.

2.1 The modelling tool and data used

2.1.1 The FAIR world model

The FAIR 2.1 world model (Den Elzen, 2005; Den Elzen et al., 2007) is essentially a country-version of the FAIR 2.1 (region) model, which is a policy-decision support tool for analysing emission allowances and abatement costs at the level of 17 regions[6] (Den Elzen and Lucas, 2003; 2005). The expansion of the model to the level of countries has been a major step forward, and one that has only recently (2005) become possible as accurate and reliable data of baseline emission scenarios at the level of all world countries were not available prior to 2005, and downscaling methods have been the subject of criticism (see Den Elzen, 2005; see Pitcher, 2004; Van Vuuren et al., 2007) in that they have led to unrealistic results for some countries (in particular the one using the regional trend, as used by Gaffin et al., 2004; Höhne et al., 2003; Höhne et al., 2005). The model employed here uses a recently developed new downscaling method whose results are more reliable (Van Vuuren et al., 2007), as described below.

[6] More specifically, Canada, USA, OECD Europe, Eastern Europe, Former Soviet Union countries, Oceania and Japan (Annex I regions); Central America, South America, Northern Africa, Western Africa, Eastern Africa, Southern Africa, Middle East & Turkey; South Asia (incl. India), East Asia (incl. China), South-East Asia (non-Annex I regions) (IMAGE-team, 2001).

Table 1 Main characteristics of the *Triptych 7.0* approach.

Sector	**Approach selected**	**Data needs**	**User choices**
General	**Definition**		
Target year	2010–2050 (2051–2100 are also calculated, but only for illustrative purposes)		
Annex I countries emission level in 2010	- Kyoto countries: same share of sectors in 2010 as in baseline scenario - USA reaches its national target; Australia follows its baseline emissions.		
Non-Annex I countries	Sustainable development policies and measures (SD-PAMs) or no-lose targets: before non-Annex I countries participate in the convergence trajectory ('differentiated convergence'), they are committed to SD-PAMs or no-lose targets, which are implemented in the model by a uniform percentage reduction for all sectors. More specifically, reduction below baseline linear increase from 1% in 2010 up to a maximum level in 2020, and constant afterwards (differs slightly among sectors; see section 2.2).		Maximum percentage reduction of baseline emissions
Kyoto GHGs	CO_2 , CH_4, N_2O, HFCs (sum), PFCs (sum) and SF_6		• Excluding LULUCF CO_2 emissions
Countries	Up to 224 (dependent on data availability)		
Base-year emissions	The data are chosen as follows: (1) IEA data (CO_2 emissions from fossil fuel combustion) (IEA, 2005a); (2) EDGAR data (www.mnp.nl\\edgar) (CO_2 (other than from fossil fuel combustion, excluding LULUCF), CH_4, N_2O, HFC, PFC and SF_6 emissions).		
Baseline scenario	IMAGE 2.3 IPCC scenarios A1B, A1f, A1T, A2, B1, and B2 are used consistently throughout the calculations, i.e. all required scenario elements are taken from the same scenario.		• Choice of scenario
Convergence year	Starting of the convergence, convergence year and final reduction year differentiated for countries of four country groups (Box 1).		• Starting year • Convergence year • Final reduction year
Industry sector ('Energy: Manufacturing Industries and Construction' plus 'Industrial processes' as one sector (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6)			
Growth rates of industrial production	The growth rates used are derived from the energy consumption in the industrial sector of the IMAGE 2.3 scenarios.	Industrial production growth rates for several sectors	
Energy efficiency	Energy efficiency index (EEI) converges to convergence level and subsequently further improves over time up to the EEI level in the reduction year.	Initial EEI for regions (taken from Kuramochi,(2006)	• EEI level in convergence year • EEI level in reduction year
Domestic sectors (CO_2, CH_4 and N_2O emissions from fossil fuel combustion from the residential, commercial, agriculture and (inland) transport sectors and fluorinated GHG (F-gas) emissions from a range of sources (semi-conductors, refrigeration, air conditioning equipment, fire extinguishers and aerosol applications).			
Convergence	Linear convergence of per capita emissions	Population (UN, 2004)	• Convergence level
	Annual reduction rate per capita domestic emissions after convergence		• Reduction rate after convergence
Power sector (CO_2, CH_4,N_2O, HFCs, PFCs and SF_6 emissions from electricity and heat production)			
Production growth rates	The growth rates used are derived from the energy consumption in the power	Electricity demand derived from IMAGE	

Sector	Approach selected	Data needs	User choices
	sector of the IMAGE 2.3 scenarios.	2.3	
Method	CO_2 per kilowatt hour per fuel converges to convergence level, and subsequently further improves over time up to the level in the reduction year.	Current emission factors and shares per fossil fuel type, from IEA (2005a)	• Convergence and reduction level of emissions factors per fossil fuels
	Decrease of the shares of coal and oil in energy consumption		• Reduction of shares of coal and oil
	Electricity end use efficiency improvements		• Annual electricity end use efficiency improvements
Fossil fuel production	Percentage reduction of baseline emissions in convergence and final reduction year	Baseline scenario emissions	• Reduction percentage in convergence and reduction year
Agriculture	A technical, cost-effective emission reduction potential compared to the baseline scenario is assumed, accounting for activity growth and progress in animal and crop development. Different reduction potentials for countries with lower income are applied compared to countries with higher income.	Baseline scenario emissions	• Reduction percentages compared to baseline scenario in convergence and reduction year for two groups of countries
Waste	Linear convergence of per capita emissions to *x* tCO_2-eq. per capita in (differentiated) convergence year	Population	• Reduction below base-year per capita emissions in convergence year

2.1.2 Data

For the historical data this report uses different data sources. The base-year (2000) population data are provided by the UN World Population Prospects (UN, 2004). The national per capita income levels in the base-year, expressed in purchasing power parity in U.S. dollars (PPP$),[7] are based on the 2004 database World Development Indicators (WorldBank, 2004). The historical (1990–2003) sectoral countries' GHG emissions (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6) are based on the IEA and EDGAR databases, i.e.:

1. CO_2 emissions from fossil fuel combustion for the period 1990–2003 as published by the International Energy Agency (IEA, 2005a);
2. CO_2 (other than from fossil fuel combustion, excluding LULUCF CO_2 emissions), CH_4, N_2O, HFC, PFC and SF_6 emissions for the period 1990–2000 from the EDGAR database version 3.2 (Olivier et al., 2005).

The CO_2 emissions from the IEA dataset were chosen, as this dataset is the most comprehensive one available at the present time, and the emissions contained in it are

[7] The Purchase Power Parity (PPP) is an indicator of the GDP per capita and is based on the relative purchasing power of local currencies in various regions, i.e. the value of a dollar in any country or, in other words, the dollars needed to buy a set of goods compared to the amount needed to buy the same set of goods in the USA.

calculated from official energy balances provided by the countries. This dataset does not include process CO_2 and non-CO_2 emissions,[8] and the only global dataset available for these is the EDGAR database (for the years 1990, 1995 and 2000). CO_2 emissions from land-use change are excluded in this analysis, but these could have been chosen from Houghton (2003).

The emission sectors distinguished are:

Sectors	IPCC	EDGAR\IEA
Industry:		
Industry (excluding coke ovens, refineries, etc.)	1A2	F10
Non-energy use and chemical feedstocks (CO_2 only)	1A2 or 2B,C	F60
Iron and steel	2C1	I10
Non-ferro metals	2C3,5	I20
Chemicals	2B	I30
Solvent use/miscellaneous	3	I70
Pulp and paper	2D1	I50
Cement production	2A1	I41
HFC, PFC and SF_6 use from a range of sources (semi-conductors, industrial refrigeration and air conditioning equipment)	2F6, 2F1, 2F8, 2F2, 2F7, 2C, 2F6, 2C3,	H11, H12, H14, H21, H24,H27, H28, H31, H35, H40, H45, H50, H55, H60
Electricity		
Power generation (public and auto; including co-generation)	1A1a	F20
Other transformation sector (refineries, coke ovens, gas works, etc.)	1A1b,c	F30
Domestic		
Residential, commercials and other sectors (RCO)	1A4	F40
Transport road	1A3b	F51
Transport land non-road (rail, inland water, pipeline and non-specified)	1A3c,d-ii,e	F54
HFC, PFC and SF_6 use from a range of sources (domestic refrigeration and air conditioning equipment, fire extinguishers, solvents and aerosol applications)	2F3, 2F1, 2F4, 2F5,	H13, H22, H23, H25, H26
Fossil fuel production		
Coal production+ (including CH_4 recovery)	1B1	F70
Oil production, transmission and handling	1B2a,c	F80 (F81, F82, F83)
Gas production and transmission	1B2b	F90 (F91, F92)
Agriculture (non-energy related emissions)		
Arable land (fertilizer use)	4D	L10
Rice cultivation	4C	L15
Animals (enteric fermentation)	4A	L20
Animal waste management (confined N_2O; all CH_4); Animal waste (deposited to soil - N_2O)	4B	L30, L60
Biomass burning	5A1, 4F	L41, L43
Savannah burning	4E	L42
Indirect fertilizer/Indirect animal waste	4D	L75
Biological N-fixation	4D	L50
Fuel wood burning	5A2,3, 5B1	L44, L45
Waste (waste disposal and processing)		
Landfills (including CH_4 recovery)	6A1,2	W10
Wastewater	6B1,26B2	W20, W30 (W39),
Waste incineration (non-energy)	6C	W40

[8] Note that CO_2 emissions from the IEA do not include process emissions from cement production.

Emissions up to 2010 are estimated as follows:

- It is assumed that Annex I countries (excluding the USA and Australia) implement their Kyoto targets by 2010, including those Annex I countries with baseline emissions in 2010 much less than their Kyoto targets, i.e. countries with excess emission allowances (‘hot air’).
- It is assumed that the reductions necessary to meet the Kyoto target are achieved in all sectors equally: the sectoral reference emissions in 2010 are chosen and reduce emissions of all sectors by the same factor so that the Kyoto targets are met.
- The years from the last available year up to 2010 are linearly interpolated.

All Non-Annex I countries follow their baseline scenario up to 2010.

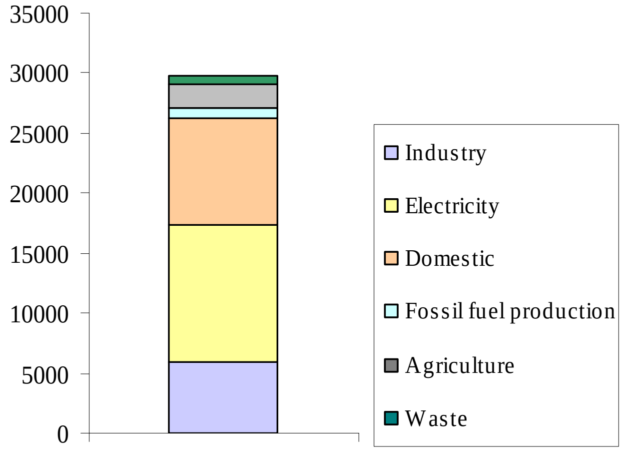

Figure 1 Global GHG emissions of sectors in 2003 (in $MtCO_2$) (excluding international aviation and marine bunkers and land-use CO_2 emissions).

For the future baseline emissions, the downscaling methodology of Van Vuuren et al. (2007) is applied on the updated IMAGE 2.3 IPCC-SRES scenarios, downscaling from the 17 world regions towards 224 countries. This report distinguishes the socio-economic driving forces of population size and per capita income levels as well as technological improvements, such as energy efficiency improvements and the type of fuels used, which is equitable to emission intensity (emissions per unit of GDP):

- For downscaling of the population, the relative sizes of countries in the long-range population projections of the UN (2004) are used.
- For downscaling per capita income and emission intensity (partial), convergence of the units to the average regional number is assumed, while ensuring that the total of the elements complies with the pathway of the larger unit.
- For the energy- and industry-related sectors (industry sector, domestic sector, power sector and fossil fuel production), relative changes in the three components (population, per capita GDP and emission intensity) compared to the base-year (2000) are used to determine the future sectoral emissions per country.

- For the agriculture and waste sectors, simple linear downscaling is used (regional emission trend for all countries within the region), as these sectors are only loosely linked to consumption and much more closely related to production levels.

2.2 Differentiated participation

In the Triptych 7.0 approach, convergence by ‘common but differentiated responsibilities’ is implemented. This means that all convergence trajectories in the methodology are based on a ‘common convergence’, but are ‘differentiated’ in time in that developing countries have the same obligation as developed countries to reduce emissions, but this obligation is delayed and conditional to the actions of the developed countries (Höhne et al., 2006a). More specifically, Annex I countries’ per capita emissions converge within, for example, 40 years (2010–2050) to a specific uniform per capita emissions level. Individual Non-Annex I countries’ per capita emissions also converge to the same level within, for example, 40 years, but starting when their per capita emissions are a certain percentage above the global average. Until that point is reached, Non-Annex I countries commit to policies and measures with a focus on their sustainable development objectives (Baumert and Winkler, 2005; Winkler et al., 2002)..

Two concerns often voiced in relation to the previous versions of the Triptych approach have been eliminated from Triptych 7.0. In the new Triptych 7.0 approach, developing countries are required to reduce emissions but in a delayed approach compared to Annex I countries; this condition is more compatible with the ‘common but differentiated responsibilities’ principle of the Climate Convention. The delayed participation also ensures that least developed countries are treated differently compared to the other countries, as a result of their delayed participation.

The calculations assume the following *differentiated* convergence of emissions for the developing countries: in accordance with the work of the South–North Dialogue Proposal of Ott et al. (2005), developing countries (i.e. Non-Annex I countries) are divided into four country groups on the basis of an index composed of indicators for responsibility (cumulative energy CO_2 emissions/capita in the last decade), capability (GDP-PPP/capita) and potential to mitigate (energy GHG emissions/GDP and GHG emissions/capita). These are (Box 1):

1. the newly industrialized countries (NICs; such as South Korea, Saudi Arabia, Singapore);
2. the rapidly developing countries (RIDCs, such as Argentina, Brazil, China, Malaysia, Mexico, South Africa);
3. the other developing countries (Other DCs; such as like Egypt, India, Indonesia, Nigeria, Pakistan);
4. the least developing countries (LDCs; such as Afghanistan, Bangladesh, Tanzania, Zambia).

Box 1 Countries in different country groups (see Figure 2)

Newly Industrialized Countries (NICs): Bahrain, Brunei, Cuba, Israel, Kazakhstan, Korea (South), Kuwait, Qatar, Saudi Arabia, Singapore, Suriname, Trinidad & Tobago, Turkmenistan, United Arab Emirates, Uzbekistan.

Rapidly Developing Countries (RIDCs): Algeria, Antigua & Barbuda, Argentina, Bahamas, Barbados, Belize, Bosnia & Herzegovina, Botswana, Brazil, Chile, China, Colombia, Costa Rica, Cyprus, Dominican Republic, El Salvador, Fiji, Grenada, Guyana, Iran, Jordan, Lebanon, Malaysia, Malta, Mauritius, Mexico, Oman, Panama, Peru, Philippines, Saint Kitts & Nevis, Saint Lucia, Saint Vincent & Grenadines, South Africa, Thailand, Tunisia, Uruguay.

Other Developing Countries (DCs): Armenia, Azerbaijan, Bolivia, Cameroon, Congo, Cook Islands, Ivory Coast , Dominica, Ecuador, Egypt, Gabon, Georgia, Ghana, Guatemala, Honduras, India, Indonesia, Jamaica, Kenya, Kyrgyzstan, Libya, Macedonia, Former Yugoslav Republic (FYR), Moldova, Mongolia, Morocco, Namibia, Nicaragua, Nigeria, Pakistan, Papua New Guinea, Paraguay, Seychelles, Sri Lanka, Swaziland, Syria, Tajikistan, Venezuela, Vietnam, Zimbabwe.

Least Developing Countries (LDCs): Afghanistan, Angola, Bangladesh, Benin, Bhutan, Burkina Faso, Burundi, Cambodia, Cape Verde, Central African Republic, Chad, Comoros, Congo Dem. Republic , Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gambia, Guinea, Guinea-Bissau, Haiti, Kiribati, Laos, Lesotho, Liberia, Madagascar, Malawi, Maldives, Mali, Mauritania, Mozambique, Myanmar, Nepal, Niger, Rwanda, Samoa, Sao Tome & Principe, Senegal, Sierra Leone, Solomon Islands, Somalia, Sudan, Tanzania, Togo, Tuvalu, Uganda, Vanuatu, Yemen, Zambia.

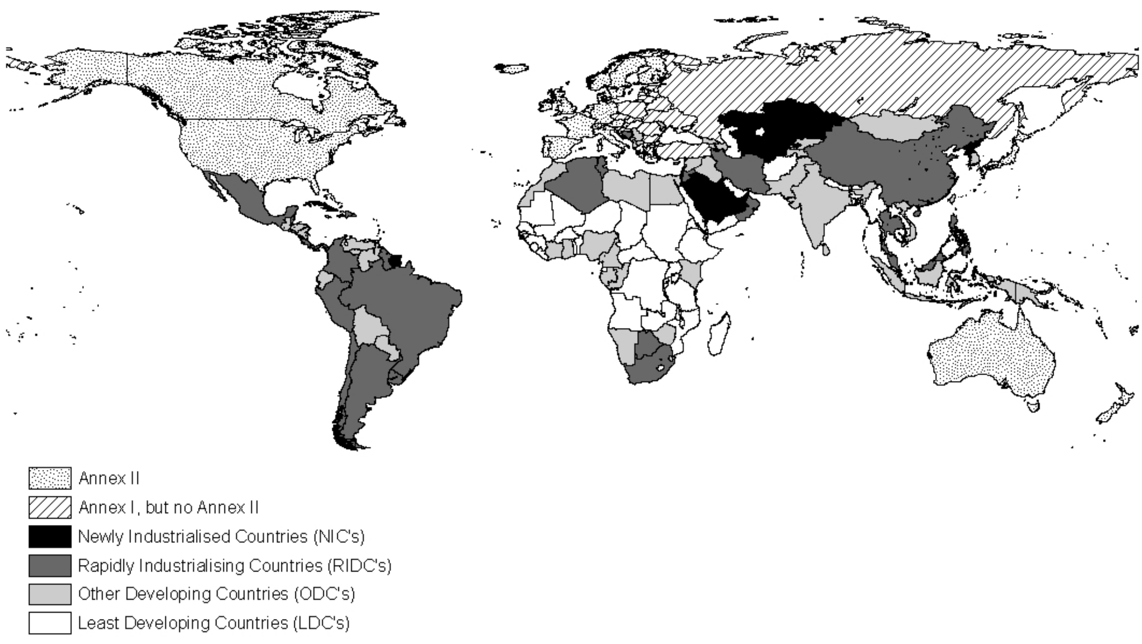

Figure 2 Membership of countries in groups: Annex II countries, Annex II but no Annex I countries, NICs, RIDCs, other DCs and LDCs. Source: Ott et al. (2005).

For simplicity, this study assumes that the composition of the country groups does not change.[9] The starting year of the convergence is now differentiated and defined in the scenarios presented in Chapter 3 – for example, 2010 for the NICs, 2020 for the RIDCs, 2030 for Other DCs and 2040 for LDCs – while the convergence period for all countries remains the same.

Prior to participation, the developing countries adopt SD-PAMs or no-lose targets, depending on their needs and their state of development.

- In general, the SD-PAMs must be government actions that both have development and GHG emissions benefits (Winkler et al., 2002). SD-PAMs do not necessarily reduce emissions in absolute terms, as energy use and emissions in developing countries will need to grow to meet the requirement of sustainable economic development. Examples of SD-PAMs are improvements in energy and energy conservation and a switch to low carbon fuels, both of which provide sustainable development benefits in terms of energy security, reduced air pollution, higher employment levels and reduced costs for consumers and companies (Baumert and Winkler, 2005).
- No-lose targets set a limit for total emissions in a target year. If this target is exceeded (real emissions are below the target), the additional emission allowances can be sold on the carbon market. If the target is not met (real emissions are above the target), no additional rights have to be bought. As such, no-lose targets are seen as an incentive for developing countries to participate in the system, but it is an option that requires an enhanced ability to quantify emission and emission reductions.

In the Triptych 7.0 approach, the reduction targets of the SD-PAMs and the no-lose targets are implemented as a national reduction factor compared to the reference case. Developing countries will reduce their emissions by roughly 10% compared to their baseline emissions within the first 10 years after 2010; more specifically, the reduction below the baseline linear increases from 1% in 2010 to 10% in 2020, and remains at 10% thereafter. This is in line with the results of two other studies that analysed the impact of first reduction activities in developing countries (Höhne and Moltmann, 2007; Ogonowski et al., 2006)and found these to be in the order of 10–15%. For all sectors except power and industry, this study assumes emission to be 10% below baseline emissions within 10 years. The power and industry sectors were treated differently since detailed data are necessary when countries participate at a later stage:

- Power sector: the shares of energy sources in the year when the country participates are assumed to stay constant for the period 2004 until the differentiated starting year; emissions per kilowatt hour decrease by 1% per year over a 10-year period compared to baseline. This is roughly equivalent to a 10% emission reduction compared to the baseline in 10 years.

[9] Den Elzen (2005) and Den Elzen et al. (2007) analysed how the composition changes under the South-North Dialogue proposal compatible with meeting different long-term greenhouse concentration targets.

- Industry sector: efficiency improvements increase by 1% per year, which – over a 10 year period – is roughly equivalent to a 10% emission reduction compared to the baseline.

2.3 Industry sector

In the Triptych 7.0 approach the industrial sector consists of the manufacturing industry and construction. Due to the lack of available data, the industrial sector is handled in its entirety – i.e. energy-intensive and light industry are not treated differently.

The general concept is that the physical production of goods is growing while at the same time energy efficiency is improving. This study used the methodology of Groenenberg et al. (2004), but now with differentiated convergence.

Future production – The growth of industrial production is based on *energy consumption in industry* (excluding electricity) taken from the IMAGE 2.3 IPCC-SRES scenarios. In this way, Triptych 7.0 accounts better for structural changes in the industrial sector as well as for autonomous baseline energy efficiency improvements, as described in detail in Van Vuuren et al. (2006b), compared to the earlier used growth in monetary value as “industrial value added”. If Western Europe is taken as an example, the total efficiency improvement for the IMAGE 2.3 B2 IPCC-SRES scenario (used for the default calculations) is 0.8% per year over the period 2000–2050, with 0.7% of this due to energy efficiency improvements and 0.1% due to structural changes. For China, the total improvement rate becomes as high as 6%, of which 2.5% derives from energy efficiency improvements.

Energy intensity – For the energy-intensity levels, a worldwide convergence in energy efficiency levels of all countries over time is assumed (Groenenberg, 2002). A convenient indicator for energy efficiency is the EEI (Phylipsen et al., 1998). This index is defined as the ratio between the specific energy consumption (SEC) (energy consumption per tonne of product) for each region divided by the theoretical SEC using best current practices or best available technologies. For example, an EEI of 1.05 in a region means that the average SEC is 5% higher than the reference level, so that 5% of energy could be saved in the given sector structure[10] by implementing the best practice level technology. The SEC of a package of energy-intensive commodities is aggregated in the EEI, resulting in aggregated EEIs over the various subsectors in the energy-intensive industry for all countries, each representing a relative measure of the average efficiency of the energy-intensive industry in that specific country. For a further description of the EEI, see Appendix B. This study has used the recently updated values based on the work of Kuramochi (2006) and Höhne et al. (2006b) as summarized in Table 3.

[10] The sector structure can be defined as being determined by the mix of activities or products within a sector. This mix may well influence the reference-specific energy consumption level (Phylipsen et al., 1998).

Compared to the EEI data used in the earlier study of (Groenenberg, 2002), the EEI data for the iron and steel, pulp and paper, cement and petrochemical industry[11] have been updated for the years 2000–2003 with improved data coverage, while the petroleum refining subsectors are newly added. The aluminium subsector considered by Groenenberg is omitted due to the lack of up-to-date energy consumption data. Various energy data sources are used, while the consistency of the data is carefully examined, as summarized in Table 2 (for further details, see Kuramochi (2006) and Höhne et al. (2006b)).

As an example, Figure 3 presents the EEI data for the sector iron and steel for the top 20 steel-producing countries. The numbers preceding the country names present the crude steel production ranking in 2000. Among the top 20 producers, the EEIs ranged between 1.2 and 2.9, which means that the worst energy efficient country is nearly 2.5-fold less energy efficient than the best energy efficient country. South Korea can be seen to have the best EEI, 1.16, followed by Japan (1.2), France (1.4) and Germany (1.4). The EEIs for the remaining countries are given in Table 3. South Africa can be seen to have the lowest energy efficiency with an EEI of 2.9; other energy-inefficient countries with high EEIs include Russia, China and Poland.

Table 2. Sources used for the calculation of the Energy Efficiency Indices (EEIs) of Kuramochi (2006) and Höhne et al. (2006b).

Sector	**Production**	**Energy consumption**	**Best practice specific energy consumption (SEC)**	**Further details, see:**
Iron and steel	International Institute for Iron and Steel (IISI, 2005)	IEA's Energy Balances (IEA, 2005c; 2005d)	Farla and Blok (2001); Kim and Worrell (2002)	Kuramochi (2006)
Pulp and paper	Food and Agriculture Organization of the United Nations (FAOSTAT, 2006)	Various national statistics, see Kuramochi (2006)	Farla et al. (1997)	Kuramochi (2006)
Cement	National statistics and data from ENCI (2002)	IEA's Energy Balances (IEA, 2005c; 2005d)	Kim and Worrell (2002)	Höhne et al. (2006b)
Petrochemical industry	Phylipsen et al. (2002)	IEA's Energy Balances (IEA, 2005c; 2005d)	Phylipsen et al. (2002)	Phylipsen et al. (2002)
Petroleum refineries	Actual crude intake (IEA, 2005b)	IEA's Energy Balances (IEA, 2005c; 2005d)	Höhne et al. (2006b)	Höhne et al. (2006b)

[11] The designation Petrochemical industry refers to ethylene production, whereas the term petrochemical refineries refers to crude oil refining and cracking, which is a process to produce products from which ethylene is made.

Table 3. The EEIs at the country level. Source: Kuramochi (2006).

		Iron and steel 2000			Pulp and Paper 1999-2000			Cement 2003			Petrochemical 1995			Petroleum refinery 2000			Ammonia 1994-1996			Aggregated EEI	Regional EEI
		Energy intensity (GJ/t)	EEI	Production (Mtonnes)	Energy intensity (GJ/t)	EEI	Production (Mtonnes)	Energy intensity (GJ/t)	EEI	Production (Mtonnes)	Energy intensity (GJ/t ethylene)	EEI	Production (Mtonnes)	Energy intensity (GJ/toe)	EEI	Production (Mtoe)	Energy intensity (GJ/toe)	Energy index	Production (Mtoe)		
West Europe	Austria	19.1	1.5	5.7	17.2	1.0	4.1				33.8	1.5	0.2				34.1	1.2	0.4	1.2	1.3
	Belgium	21.1	1.5	11.6	17.2	1.2	1.7				34.9	1.6	1.5				37.8	1.4	0.8	1.5	
	Denmark	11.8	2.3	0.8																2.3	
	Finland	19.7	1.5	4.1	26.9	1.2	12.9				33.8	1.6	0.1							1.2	
	France	17.7	1.4	21.0	16.2	1.2	9.6	3.3	1.0	20.0	33.7	1.5	3.0				37.8	1.4	1.5	1.3	
	Germany	17.0	1.4	46.4	13.4	1.2	16.7	3.0	0.9	30.0	32.9	1.5	4.2				37.8	1.4	2.6	1.3	
	Greece	12.2	1.6	1.1																1.6	
	Ireland	11.1	1.9	0.4													38.7	1.4	0.4	1.5	
	Italy	14.9	1.5	26.8	14.5	1.3	8.6	3.5	1.0	38.0	32.4	1.4	1.7				37.8	1.4	0.4	1.3	
	Luxembourg	9.7	1.4	2.6																3.6	
	Netherlands	18.0	1.2	5.7	11.7	1.2	3.3				32.8	1.5	2.6				34.0	1.2	2.5	1.5	
	Portugal	15.1	1.5	1.1	42.7	1.2	1.2				32.4	1.4	0.3				42.4	1.5		1.3	
	Spain	15.6	1.8	15.9	16.9	1.1	4.4	3.3	1.0	42.0	32.4	1.4	1.0						0.5	1.3	
	Sweden	19.6	1.6	5.2	33.3	1.4	10.1				33.8	1.6	0.2							1.4	
	United Kingdom	21.0	1.6	15.2	11.2	1.1	6.2				33.8	1.6	1.2				38.7	1.4	1.1	1.9	
	Norway										33.8	1.6	0.2						0.3	1.6	
	Switzerland	10.7	1.5	1.0																1.5	
	EU_15		1.5					3.1	0.9	69.0				2.6	1.2	671.6					
East Europe	Czech Republic	23.3	2.0	6.2	36.5	1.6	0.8													1.9	1.8
	Hungary	18.0	1.5	1.9																1.5	
	Poland	22.9	2.1	10.5				3.2	0.9	12.0									1.9	1.8	
	Slovakia	24.1	1.7	3.7	22.8	1.2	0.9													2.1	
	Bulgaria	25.5	2.5	2.0																2.5	
	Romania	31.8	2.8	4.7																2.8	
	Rest of Central/East Europe							4.3	1.2	37.0											
North America	Canada	17.7	1.5	16.6	53.5	2.0	20.9	4.9	1.4	14.0				3.5	1.3	95.3	32.6	1.2	3.7	1.7	1.7
	USA	18.5	1.7	101.8	34.0	1.7	81.9	6.1	1.7	94.0	33.9	1.6	10.0	4.3	1.5	838.5	40.1	1.4	13.1	1.6	1.6
Latin America	Mexico	20.0	1.6	15.6				4.0	1.1	32.0				5.0	3.0	66.0				1.7	1.7
	Argentina													4.6	2.9	26.7				1.7	
	Brazil	27.2	1.7	27.9	47.5	1.7	6.5	3.5	1.0	38.0				2.0	1.9	82.4				1.6	
	Chile	18.7	1.5	1.4																1.5	
	Colombia							5.2	1.5	7.0										1.5	
	Peru							4.9	1.3	6.0										1.3	
	Venezuela	49.3	2.1	3.8				5.2	1.4	7.0										1.9	
	Rest of South America							4.5	1.2	32.0											
FSU	Kazakhstan	32.6	2.5	4.8																2.5	2.4
	Russia	34.2	2.7	59.1				6.0	1.8	41.0				3.5	2.2	178.8				2.5	
	Ukraine							6.1	1.8	9.0										1.7	
Middle East	Iran							5.2	1.3	30.0				16.6	8.7	11.0				2.4	2.3
	Turkey							4.9	1.3	33.0										1.4	
	Saudi_Arabia							4.7	1.3	23.0				8.4	4.3	89.9				3.3	
	Rest of Middle East							4.9	1.3	30.0							45.5	1.6	1.7		
Japan	Japan	16.6	1.2	106.4	19.2	1.2	31.8	3.1	0.9	71.0	25.1	1.2	2.5	2.1	0.8	213.9				1.1	1.1
East Asia	South_Korea	13.7	1.2	43.1				3.5	1.0	59.0	26.1	1.2	1.3	1.5	0.8	128.0				1.0	1.7
	Taiwan	18.1	1.4	16.9				4.4	1.1	18.0										1.3	
	China	35.0	2.1	127.2				5.0	1.5	813.0				4.5	4.2	203.1				1.9	
SE Asia	Indonesia	28.7	2.1	2.8				5.1	1.3	35.0				2.5	2.1	51.5				1.5	1.5
	Malaysia							4.6	1.2	17.0										1.2	
	Thailand	23.5	2.6	2.1				4.5	1.2	32.0				2.7	1.8	35.6				1.4	
South Asia	India	32.7	2.0	26.9	57.5	2.9	3.8	4.6	1.2	110.0				2.8	2.8	105.7	39.6	1.4	9.5	1.6	1.6
	Pakistan																39.6	1.4	11.6	1.4	
	Rest of Asia							4.7	1.2	66.0											
Africa	Egypt							5.6	1.3	29.0										1.3	2.1
	Algeria	37.7	2.6	0.8																2.6	
	South_Africa	44.4	2.9	8.5	74.8	3.0	2.0	4.6	1.2	9.0				8.0	2.2	25.5				2.7	
	Zimbabwe	61.0	3.7	0.3																3.7	
	Rest of Africa							4.8	1.2	14.0											
Oceania	Australia	24.3	1.4	7.1				4.2	1.2	8.0							47.4	1.7	0.5	1.5	1.5
	NewZealand	31.6	2.2	0.7				4.2	1.2	1.1										2.2	

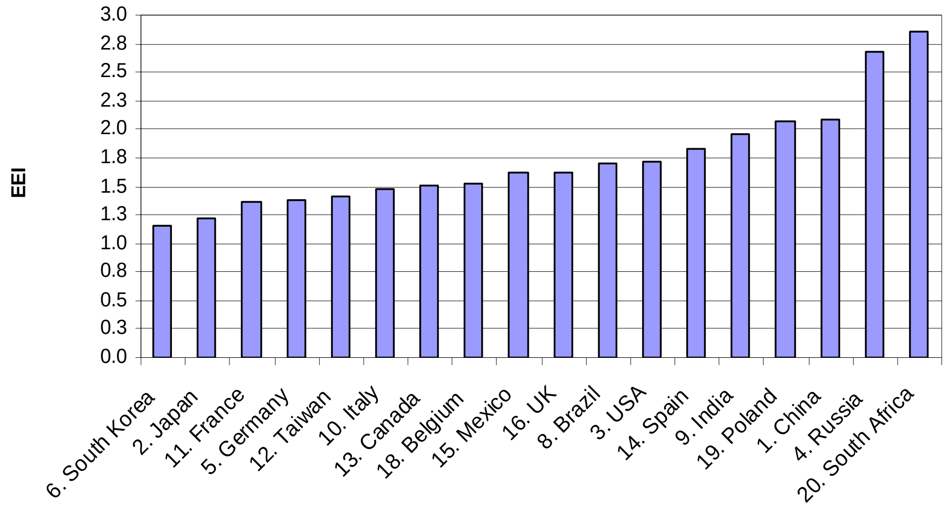

Figure 3 Energy Efficiency Indices (EEI) of the top 20 steel producing countries for year 2000, including secondary steel making in electric furnaces. Source: Kuramochi (2006).

It is very possible that some subsectoral EEIs in Table 3 have values below 1 (for example, for the cement sector for Japan) through the application of non-conventional technologies with significantly low SECs. The aggregated EEI of the regions ranges between 1.1 (Japan) and 2.4 (Russia). Due to an improved coverage of the industrial energy consumption, the regional aggregated EEIs for some regions have significantly changes from those reported by Groenenberg (2002) (Table 4). The results of Kuramochi (2006) indicate larger differences in regional industrial energy efficiencies.

Table 4 Comparison of aggregated EEIs in the energy intensive industry of the regions.

Region	EEI – Groenenberg (2002)	EEI – Kuramochi (2006)
Canada	1.3	1.7
USA	1.7	1.6
Latin America	1.5	1.7
Africa	1.6	2.1
Western Europe	1.2	1.3
Eastern Europe	1.7	1.8
Russia	2.0	2.4
Middle East	1.6	2.3
South Asia	1.7	1.6
East Asia	1.9	1.7
South-East Asia	1.6	1.5
Oceania	1.7	1.5
Japan	1.3	1.1

The *Triptych 7.0* methodology assumes that the EEI converges linearly to a convergence level in a given year of convergence. This convergence is differentiated for the different country groups, as described in section 2.2, with the same starting year for countries within the four country groups (Box 1) and a common convergence period for all countries. This common level then decreases further as time progresses.

The methodology of considering energy intensity in industry includes the incorporation of future changes in energy consumption due to technological progress or energy saving, or structural changes in the industrial sector. Changes in the emission intensity of energy due to, for example, a fuel switch, technological changes or carbon capture and storage are not included. These effects would be small in the short term but could be large in the long term.

2.4 Domestic sector

The domestic sector includes fossil fuel combustion from the residential, commercial, agriculture and (inland) transport sectors and F-gases emissions from a range of sources (refrigeration, air conditioning equipment, fire extinguishers and aerosol applications). It does not include emissions from electricity used in these sectors. The allowable GHG emissions in the domestic sectors are assumed to be primarily related to population size, since they are determined by the number of people in dwellings and at workplaces and by those needing transport, etc. Therefore, it is assumed that the GHG emissions per capita will converge differentiated (same starting years for the four groups of developing countries as described before) and linearly to the same level worldwide over the same period (e.g., 40 years). This level includes a convergence of the standard of living (e.g. number of cars, fuel use per household for space heating) and a reduction in existing differences in energy efficiency of buildings and vehicles. Groenenberg (2002) uses a medium value of 2.0 tCO_2-eq. per capita in 2050, with a range of 1.5 to 3.0 tCO_2-eq. per capita. Total emissions in the domestic sector are determined by multiplying the per-capita emissions for each year with the population for that year, according to the reference scenario.

2.5 Power sector

The electricity -production sector is treated separately because specific GHG emissions from power production vary to a large extent among countries due to large differences in their shares of nuclear power and renewables and in the fuel mix in fossil fuel-fired power plants. The potential for cutting GHG emissions arising in this sector differs accordingly. Therefore, the fuel mix in power generation is an important national characteristic to take into account in the differentiation of commitments.

The calculations of the future emissions in the power sector assume a *growth in electricity consumption* (from the IMAGE baseline), *a convergence of emissions per kilowatt hour per fuel*, a *decrease in the coal and oil shares* in the fuel mix, *an improvement in the efficiency of electricity consumption* and *a decrease in electricity consumption (demand)* of the industry and domestic sector. The last four aspects are the same for all countries:

1. *Convergence of emissions per kilowatt hour per fuel*: The emissions per fuel converge (in CO_2 per kilowatt hour) for each fuel by a differentiated year (see Table 5).
2. *Decrease in the share of coal and oil in the fuel mix*: The share of coal and oil in the mix of fuels used decrease linearly compared to the 2004 levels (for example, by 30% until 2030 and by 75% until 2050). A major proportion of this reduction can be achieved by CCS, in particular for the meeting the stringent climate targets, and by renewables. Accordingly, countries with high shares of coal and oil power stations need to reduce to a greater extent than counties which currently have a low share.
3. Annual *improvements in the efficiency of electricity consumption* (compared to the baseline electricity consumption): This is due to their convergence trajectories (for example, by 1.5% per year) (see section 3.2). This factor of decreasing demand from the industry and domestic sector is also included in the *Global Convergence Triptych* approach developed by Groenenberg et al. (2004).

The following formula illustrates how emission reductions are calculated in the first reduction phase for Annex I countries for the year 2030 under the strong scenario with a 1.5% decrease in electricity consumption and a 60% reduction in the share of coal and oil (compared to 2004 levels):

$$\begin{aligned}
&\mathrm{CO_2\ emissions}_{\mathrm{AnnexI\,2030}} = \frac{\mathrm{elec.consum}_{\mathrm{total\ 2030}}}{\mathrm{elec.consum}_{\mathrm{total\ 2004}}} \times (1-1.5\%)^{(2030-2004)} \times \\
&(\mathrm{elec.consum}_{\mathrm{coal\ 2004}} \times 600\,\frac{\mathrm{g\,CO_2}}{\mathrm{kWh}} \times (1-60\%) + \\
&\mathrm{elec.consum}_{\mathrm{oil\ 2004}} \times 450\,\frac{\mathrm{g\,CO_2}}{\mathrm{kWh}} \times (1-60\%) + \\
&\mathrm{elec.consum}_{\mathrm{gas\ 2004}} \times 300\,\frac{\mathrm{g\,CO_2}}{\mathrm{kWh}})
\end{aligned}$$

Applying these requirements and assumptions on the growth in electricity consumption, we are able to calculate the emissions that represent the limits of that specific country. For the developing countries, the same formula is applied, but again with a differentiated convergence – that is to say, the same starting years for the four country groups (such as 2020 instead of 2004) and the same convergence period for all countries (as described in section 2.2)

The approach as described above does not take into account heat production, which also contributes to emissions. According to the IEA (2005b), more than half of the power production of some countries is based on CHP. The most notable of these are the Nordic and Eastern European countries, including Denmark, Hungary, Iceland, the Netherlands, Norway, Poland, Slovak Republic, Albania, Azerbaijan, Belarus, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Russia, Tajikistan and Turkmenistan.

Accordingly, this study considers emissions from the power sector to be the sum of the emissions from electricity production, as described in the formula above, and an adjustment factor (for heat production and other statistical differences between the datasets). For future years, this adjustment factor declines at the same rate as the emissions from electricity production.

2.6 Fossil fuel production

Methane emissions from coal mining and from oil and gas production and distribution amounts to only about 5% of the total (2000) global GHG emissions; however, currently available technology can reduce this amount by around 60% compared to baseline levels in 2010 (Delhotal et al., 2006) and by up to 90% towards the end of the century. Therefore, as emissions from this sector can be reduced drastically, emissions from fossil fuel production are treated as a separate sector. The baseline emissions from this sector are assumed to be scaled with the ratio baseline emissions and Triptych emissions from the three energy-consuming sectors. An additional reduction factor further reduces the emissions so that its reduction target can be reached in a (differentiated) convergence year (for example, 70% in 2050), with the reduction continuing until it reaches its maximum for a certain year (Lucas et al., 2007)

2.7 Agriculture sector

The emissions from the agricultural sector are expected to grow substantially, mainly in accordance with population and economic growth. However, substantial emission reduction options are available at relatively moderate costs (Graus et al., 2004). Under low concentration stabilization targets, reductions as high as 50% below the baseline emissions can be reached in the OECD countries in 2050, while in the non-OECD countries a somewhat lower reduction is reached (Lucas et al., 2007). Hence, emissions are assumed to be (linearly) reduced by a certain percentage below the reference scenario in the convergence year (differentiated), following which the reduction continues until a reduction percentage in 2100 is reached. This reduction is based on Lucas et al. (2007). Two groups of countries are distinguished: Annex I countries have to reduce more than ADC and LDCs.

2.8 Waste

Emissions from waste are substantial, but many emission reduction options exist (e.g. capture of CH_4 from landfills). Hence, these emissions are treated as a separate sector. Emissions from the waste sector are assumed to converge to a per capita level in a (differentiated) convergence year. The latter is taken to be a fraction of the global per capita emissions in the base-year, using reduction potentials based on Lucas et al. (2007).

2.9 Land-use-related CO_2 emissions

Data on land-use change and forestry is difficult to estimate and to assess. Emissions from this sector are always surrounded with many uncertainties. Due to this, land-use change and forestry emissions are not included in the Triptych calculations for this report.

3 Model analysis of the Triptych approach

3.1 Baseline emissions

The baseline scenarios used in this study are based on the set of SRES scenarios developed by (Nakicenovic et al., 2000) which explores different possible pathways for GHG emissions on the basis of two major uncertainties: (1) the degree of globalization versus regionalization and (2) the degree of orientation on economic objectives versus an orientation on social and environmental objectives. The storylines of the SRES scenarios have recently been re-implemented into the IMAGE 2.3 model (Van Vuuren et al., 2006a). This study uses the IMAGE/TIMER 2.3 SRES B2 scenario (hereafter referred to simply as the IMAGE 2.3 IPCC B2 scenario), which is a medium scenario, as the central baseline scenario, while all six IMAGE/TIMER 2.3 IPCC-SRES (IMAGE 2.3 IPCC) scenarios – A1b, A1f, A1t, A2, B1, B2 – are used to show the impacts of different baseline assumptions. For the central B2 baseline scenario, energy-sector CO_2 emissions continue to rise for most of the century due to increasing coal and gas use, peaking at 18 GtC in 2080 (making the scenario a medium–high baseline compared to those presented in existing literature). Total Kyoto GHG emissions also increase, that is from a current 10 GtC-eq. to 23 GtC-eq. in 2100. As a result, by 2100, the baseline reaches a CO_2 concentration of about 730 ppm CO_2 and a GHG concentration of 850 ppm CO_2-eq.

3.2 Three technology-oriented scenarios

STRONG: Early convergence to high technology standards with a large coalition

- Basic idea: Climate change is considered by all countries to be an urgent problem, which is to be coped with through the cooperation of countries in terms of strong technology transfer.
- Main assumption: Early convergence to the present (2004) level of the best performing Annex I country (such as CO_2 emissions per kilowatt hour per fuel type) in 2030, followed by common convergence to the lowest technical sectoral target in 2050 for the Annex I countries and newly industrialized countries (NICs) (Box 1). The advanced developing countries (ADCs) follow the same convergence, but with a 5-year delay, and the least developing countries (LDCs) are given yet an additional 5-year delay.

MEDIUM: Medium convergence to high technology standards, and a delayed convergence for the developing countries

- Basic idea: Climate change is considered to be an urgent problem, but there is only a slow technological transfer from industrialized to less developed countries.

- Main assumption: Starting in 2010, Annex I countries and NICs implement a convergence trajectory to the present (2004) level of the best performing Annex I country in 2050. The ADCs implement the same convergence pathway, but with a 10-year delay, and the LDCs are given yet an additional 10-year delay.

SLOW: Slow convergence to medium technology standards, and a delayed convergence for the developing countries

- Basic idea: Climate change is not considered by all countries to be an urgent problem, and there is a slow technological transfer from industrialized to less developed countries
- Main assumption: Convergence to a target level that is about 10–15% above the present (2004) level of the best performing Annex I country in 2050, and then common convergence to the lowest Annex I sectoral target in 2100. The NICs and ADCs do the same convergence, but with 10-year delay, and the LDCs are given yet an additional 10-year delay.

3.3 Choice of model parameters

A major element of the Triptych 7.0 approach is the differentiated convergence. The EEI in industry, the emissions per energy source in the power sector and the per capita emissions in the domestic sectors converge. The starting year of the convergence, the end year and a final year up to which the level is further reduced are chosen for the different country groups. Figure 4 provides an overview of these choices for the strong, medium and slow scenario, respectively. The year 2010 is chosen as the simplified starting year following the first commitment period of the Kyoto Protocol. At the same time, this is the starting year for further action for Annex I countries and NICs in the strong and medium scenario. For the slow scenario, the NICs also enter the Triptych convergence, but 10 years later, in 2020. As described above, the implementation of measures by ADCs and LDCs is delayed compared to 2010 by 5–10 years for the former and by 10–20 years for the latter. The convergence period for all countries is set at 20 years in the strong scenario and 40 years in the medium and slow scenarios.

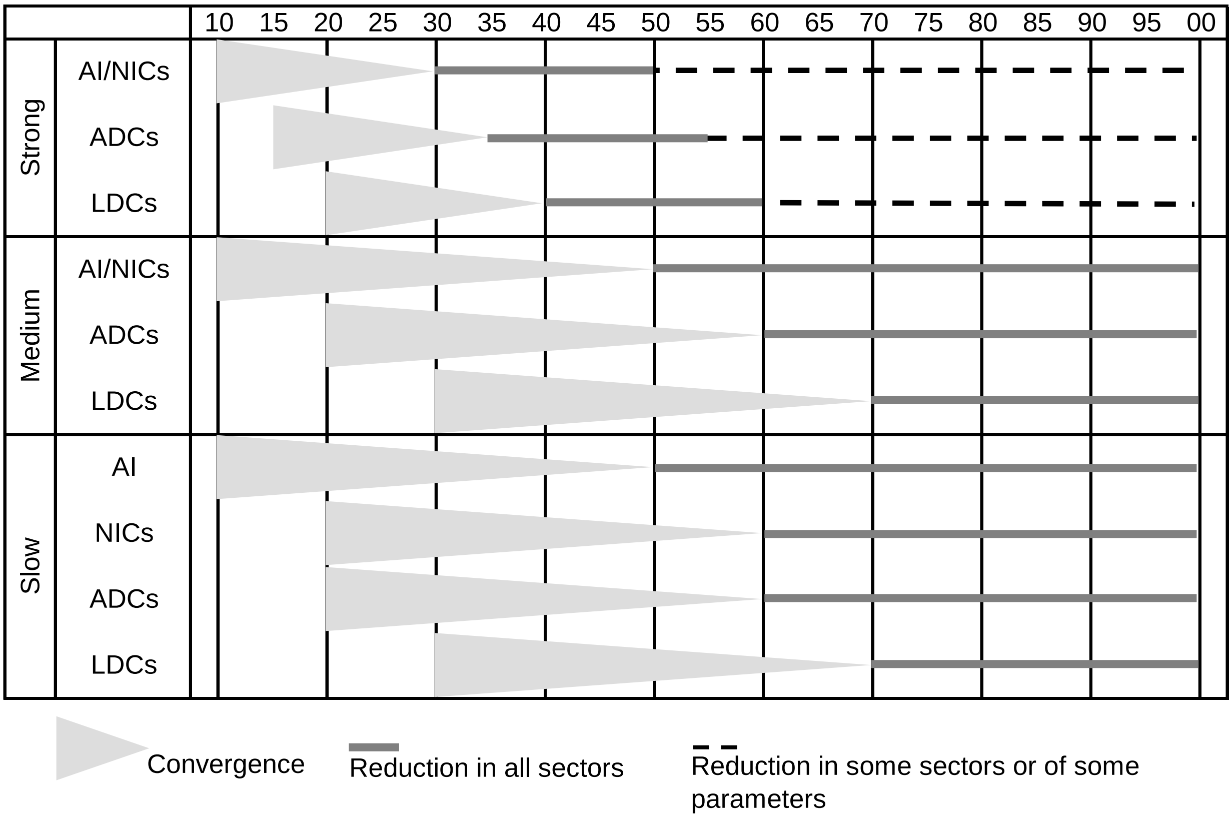

Figure 4 Starting of the convergence, convergence year and final reduction year for the scenarios and country groups, i.e. Annex I countries (AI), newly industrialized countries (NICs), advanced developing countries (ADCs) and least developing countries (LDCs) (see Box 1). The numbers at the top of the figure indicate year (2010, 2015, etc).

Table 5 presents the parameters chosen for the calculations in this report. Light-grey fields in the strong scenario include the convergence year or the respective parameter value. Medium-grey fields include the final convergence year or the respective parameter value, and dark-grey fields include (subsequent) reduction years or reduction values.

The sections below describe how the chosen parameters relate to what is possible, that is, the current status and possible future technological developments.

Table 5. Choice of model parameter for the three scenarios. Light-grey field indicates the (differentiated) convergence year and its convergence values, whereas the medium-grey field indicates the (differentiated) reduction year and its convergence year values. For the strong scenario, the dark-grey field indicates another final reduction year and the final reduction year values.

Sector	Quantity	Strong			Medium		Slow	
General	Overall effect of SD-PAMs and no-lose targets: Reduction below baseline, linear increase from 1% in 2010 up to a maximum level (given in Table ?) in 2020, and a constant level thereafter (differs slightly among sectors, see section 2.2)	Approx. -10%			Approx. -10%		Approx. -10%	
	Convergence year (first column) and final years (second and third column) for Annex I countries and NICs, with 2010 as the starting year. Convergence years for ADCs and LDCs are given in Figure 4	2030	2050	2100	2050	2100	2050	2100
Industry	Level of Energy Efficiency Indicator	1.0	0.5	0.25	0.7	0.6	1.1	0.9
Domestic	Domestic convergence level – per capita emissions in tCO_2 per capita per year	1.25			1.5		2.0	
	Annual reduction rate per capita domestic emissions after convergence		2%			1.5%		1%
Power	Convergence (left) and reduction level (right) of GHG emissions (gCO_2/kWh)							
	Coal	600	400	200	600	400	700	600
	Oil	450	300	150	450	300	500	450
	Gas	300	250	100	300	250	350	300
	Reduction in the share of coal and oil	60%	90%	95%	90%	95%	40%	80%
	Decreased electricity consumption (demand) by the industry and domestic sector	2%			1%		0.5%	
Domestic	Domestic convergence level – per capita emissions in tCO_2/capita/year	1.25			1.5		2.0	
	Annual reduction rate per capita domestic emissions after convergence		2%			1.5%		1%
Fossil fuel production	Percentage-reduction of baseline emissions in convergence and reduction year	90%	95%		90%	90%	80%	90%
Agriculture	Reduction below baseline emissions in convergence and reduction year							
	ADCs and LDCs	30%	50%		20%	30%	10%	20%
	Annex I countries and NICs	40%	50%		40%	50%	30%	40%
Waste	Reduction below base-year per capita emissions from waste in convergence year	90%			90%		70%	

3.3.1 Industry sector

In the industry sector, an increase in energy efficiency is assumed. This is included in the EEI. Data for the highest and lowest EEI values on a country basis are presented in Table 6. Several countries – Western European countries, Japan and South Korea, in particular – are already close to or even below the start-year value of 1.0 in 2030 for Annex I countries under the strong scenario, which clearly shows that – at the very least – the starting level is reachable with present-day technology. However, the envisaged reduction paths will be challenging for many countries, especially those of several Eastern European countries, Russia and New Zealand, which will have to converge early as they are Annex I countries. Important sub-sectors that influence the overall energy efficiency in energy intensive industry are iron and steel, cement as well as pulp and paper production due to their size and their energy demand.

Table 6 EEI in the energy-intensive industry for different years between 1994 and 2003. The aggregate figures include iron and steel, pulp and paper, cement, petrochemical, petroleum refineries and ammonia (Kuramochi, 2006).

	Lowest values		**Highest values**	
Aggregated EEI in industry	1–1.2	Austria, Finland, Japan, South Korea, Malaysia.	> 2.5	Luxembourg, Romania, Saudi Arabia, Algeria, Zimbabwe, New Zealand

Figure 5 shows the development of the EEI under all three scenarios between 2000 and 2100 using the information given in Table 5. It is clear that, once again, the EEI values in 2000 differ considerably among countries. Of the countries shown here, Japan and EU-25 have the highest efficiency, followed by the USA, Brazil and India, all with an EEI of around 1.7. Reduction efforts will be particularly challenging for South Africa, China and Russia under all scenarios, amounting to 3.5–4.5% per year for the strong scenario (compared to 2.5–3.5% per year for the EU-25). However, the technology is currently available to achieve this level of reduction and has been used by other countries to reach their relatively lower values.

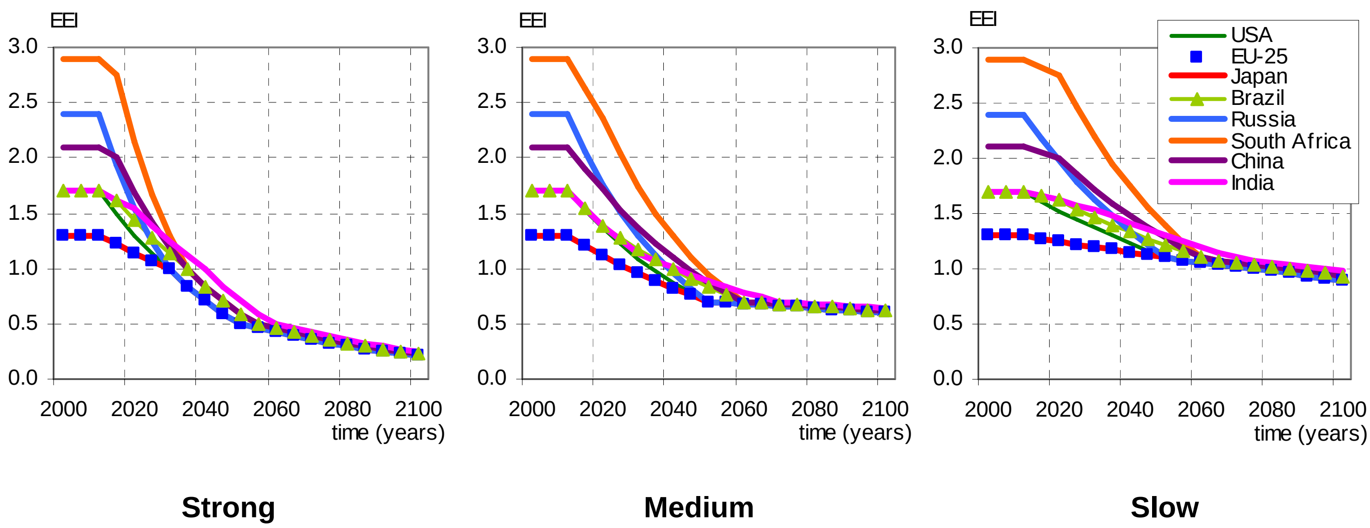

Figure 5 EEI in energy-intensive industry per country group as used for the Triptych calculations based on the parameters presented in Table 5.

In the slow scenario, today's best available technology (EEI=1) needs to be implemented by all countries in 2100. In the strong scenario, however, an efficiency that is three-fold better than today's best available technology has to be implemented. This appears to be possible given the long time horizon and historical energy efficiency improvement rates, but this level could be close to the thermodynamic limit. Groenenberg (2002) assumes the thermodynamic limit to be at about 0.3, but she bases this limit on slightly different definitions than those used here. However, changes in the emission intensity of energy as a result of a fuel switch, technological changes or CCS (not included here) could make it possible to reach the required emission reductions.

3.3.2 Domestic sector

This study compared different sources in the literature to determine a level of CO_2 emissions per capita that is reasonable for the domestic sector. Pan and Zhu (2006) come to an overall energy demand of 80 GJ per capita per year in China to fulfil basic needs and to reach a decent living standard. This includes the entire economy and, consequently, comprises more subsectors than the domestic sector as defined in Triptych. If we consider space heating, housing, public passenger transport, services, cooking and car fuel, a first approximation indicates about 35–47 GJ per capita per year. Groenenberg et al. (2004) compared different studies based on bottom-up analyses on minimum energy demand per capita. These led to an overall energy need of 32–63 GJ per capita and year (1000–2000 W per capita and year). The effect of national differences in climatic conditions and population density on minimum energy demand was not studied in these papers. This study assumes that this effect is small compared to the general uncertainties around minimum energy demand.

Table 7 provides an overview of the range of possible per capita emission levels for different per capita energy demand and different fuel mixes. The first two categories of the first column give the figures on fuel mix as assumed by Groenenberg. The last category (in italics) includes own assumptions of a higher share of renewables and other emission-free energy, a one-third share of natural gas and only very low shares of oil and coal.

Table 7 Overview of objectives for global per capita primary energy use and the resulting emissions in the domestic sector for the year 2050 (Groenenberg et al. (2004) and own estimations in italics).

Per capita energy use (GJ/cap/year)	Emission-free energy sources	Natural gas	Oil	Coal	Per capita emissions (tCO_2)
31.5 63	40%	20%	20%	20%	1.4 2.8
31.5 63	30%	30%	20%	20%	1.6 3.1
31.5 *63*	*60%*	*30%*	*5%*	*5%*	*0.9* *1.7*

The specific consumption values in Table 7 are very low compared to current actual levels, but these are possible with the implementation of currently available low-emission technology, such as low-energy-consuming houses and highly efficient cars. The current actual highest shares of energy in the domestic sector are related to space heating and transport.

Figure 6 shows the development path of per capita emissions in the domestic sector. The USA will have expended the greatest effort of all countries, given the assumptions for all parameters given in Table 5. Several developing countries, such as India, China, Brazil and South Africa, will be allowed to increase their per capita emissions up to or even above the convergence threshold.

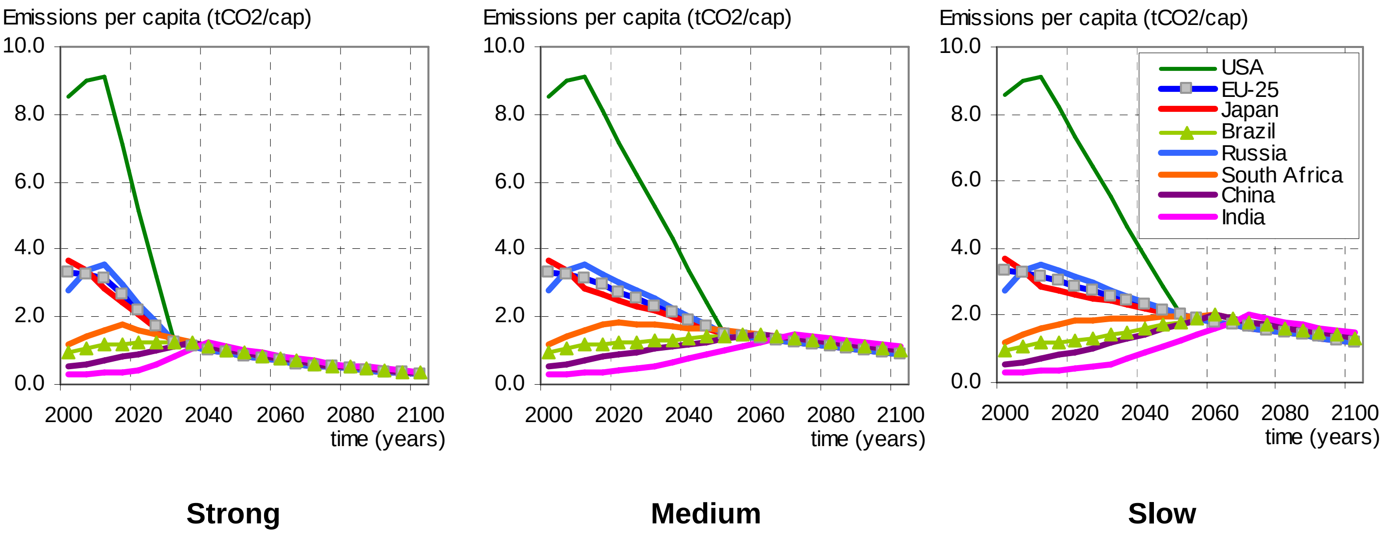

Figure 6 Domestic per capita emission levels per country group in tCO_2 as used for the Triptych calculations based on the parameters given in Table 5.

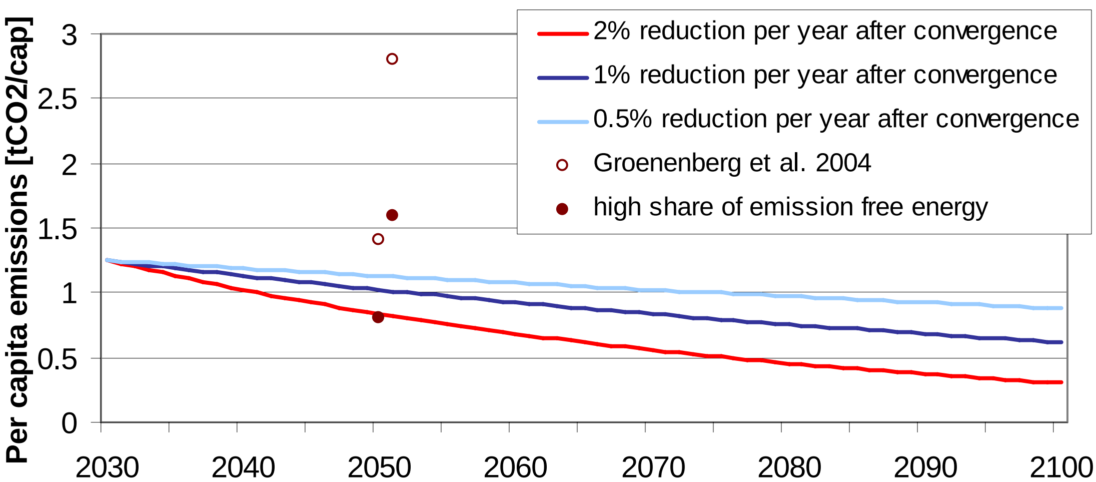

Figure 7 Possible per capita emission level for the domestic sectors for Annex I countries and newly industrialized countries used for these calculations compared to values of Groenenberg et al. (2004).

Under the strong technology scenario, domestic per capita emissions have to be very low as early as 2030 (1.25 tCO_2/capita) and even lower in 2050 (between 1 and 1–4 tCO_2/capita) (see Figure 7). Given the lifetime of buildings (50–100 years, with first needs for refurbishment after about 20 years (Bajpai et al., 2005; Blanchard and Reppe, 1998) and cars (10–15 years), a systematic change to low-energy-consuming buildings as well as changes in the car fleets and related supply infrastructure have to start within the next few years to be effective by 2030. This includes such changes as a shift of transport fuels to renewables or gas and the introduction of fuel cells with renewable fuel, among others. Stationary heat supply will have to be based on a large amount of biomass and other renewable sources, such as solar and ground heat, accompanied by the improved insulation of buildings.

3.3.3 Power production sector

The Triptych 7.0 approach has three major sets of parameters in the power production sector: convergence of emissions per kilowatt hour, reduction of coal and oil shares in the fuel mix and efficiency improvements.

1. *Convergence of emissions per kilowatt hour per fuel*:

   Current emissions per kilowatt hour (the production efficiency) in the power production sector differ substantially among countries. In addition, the difference between the current level and the final overall convergence/reduction value is considerable. The levels of selected CO_2 emissions per kilowatt hour for different fuels in 2003 presented in Table 8 give an indication of the effort that will be necessary to reach the above-mentioned values.

   The range between the countries with the lowest and the highest specific CO_2 emissions, respectively, is very large. While some countries currently have very efficient plants, others are much further in terms of CO_2 emissions reductions and are already close to the required value of emissions per kilowatt hour generated from coal, or even below that level for oil and gas. These figures demonstrate that the technology is currently available to meet the requirements set down in Table 5, even though specific emissions also partly depend on the quality of the fuel.

Table 8 Selected 2003 emission intensities per fuel (IEA, 2005a).

	Lowest values (in gCO_2/kWh)		**Highest values** (in gCO_2/kWh)	
From coal	600–700	Denmark, Sweden, Finland, Norway, Poland	>1600	Zambia, Pakistan, Brazil, Argentina
From oil	270–380	Iceland, UK, Norway, Macedonia, Sweden, Finland, South Korea	>1300	North Korea, Tanzania, Georgia, Zimbabwe
From gas	240–260	Macedonia, Denmark, Finland, Sweden,	> 800	South Africa, Brunei, Oman, Bahrain, Gabon, Bolivia

Figure 8 shows the convergence and reduction paths of emissions per kilowatt hour generated with coal between 2000 and 2100 that correspond to the values given in Table 5. The values under the strong scenario require very early action for most countries. Even so, some countries will be faced with quite a challenge to achieve the convergence levels due to the short convergence time.

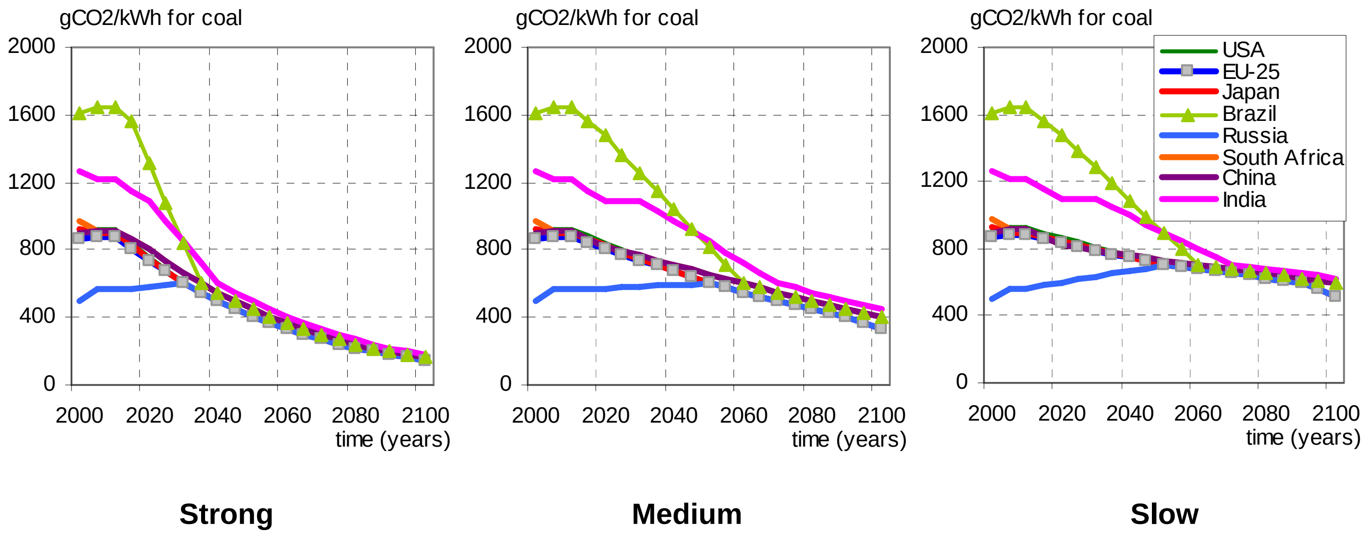

Figure 8 Emissions per kilowatt hour generated with coal per country group, as used for the Triptych calculations based on the parameters from Table 5.

2. *Reduction of oil and gas shares in the fuel mix*:

In addition to the assumption of a decrease in emission intensity per fuel, there is a second assumption of an overall reduction in oil and gas shares in the fuel mix. These reductions, as given in Table 5, are challenging, especially in the long term. High reduction rates of between 40–75% by 2050 and 80–100% by 2100 are assumed.

Due to the long lifetime of fossil power plants (about 30 years for gas, 40–50 years for coal), these reductions can only be achieved if immediate action is taken and the measures implemented during the construction of new plants or the refurbishing of old ones, or by using CCS.

Carbon capture and storage (CCS) could play an important role in achieving these reductions. This technology could become cost-effective at carbon prices of around 100–200 USD/tC (IPCC, 2005), consequently reducing mitigation costs considerably (Edmonds et al., 2004; IEA, 2004). Van Vuuren et al. (2006a) showed in their 450 ppm CO_2-eq. stabilization scenario that the contribution of CCS could be around 30– 40% of total CO_2 emissions reduced in the energy sector or 25% of total emission reductions. The largest reductions occur for coal, with the remaining coal consumption being primarily used in electric power stations using CCS.

The reduction rates will significantly increase the need for emission-free energy sources, such as renewables, renewable produced hydrogen, clean fossil energy or nuclear energy (if desired) and CCS.

3. *Decrease in the electricity consumption (demand) of the industry and domestic sector*:

   In addition to the assumption of the baseline electricity consumption, there is the assumption that there are improvements corresponding to a decreasing demand in those sectors using the electricity, that is, in the industry sector and the domestic sectors. For example, for the domestic sector, the per capita final energy use is assumed to converge to a level between 1000 and 2000 W. With respect to the EU-25, with an average domestic use of about 4000 W in 2000, this translates into an annual reduction rate of about 3.5% (aiming at 1500 W). The yearly energy efficiency improvement in the industry sector is assumed to be about 3% (see Figure 5). The share of the domestic use of the total power sector is about 50%, so the decrease in electricity consumption is about 3–3.5%.

   To keep the model simple and transparent, this study takes a rather conservative value based on the EU for the annual decrease in the electricity consumption of the industry and domestic sector: 2% per year for the strong, 1% for the medium and 0.5% for the slow scenario.

3.3.4 Fossil fuel production

A fast and extensive reduction of these emissions is even at the present time technically possible and economically valuable. Our assumption of substantial emission reductions to a small fraction of today’s emissions is therefore realistic.

3.3.5 Agriculture

Emissions from the agriculture sector are the largest contributors to non-CO_2 GHGs. The potentials for emission reductions include such options as a more efficient use of fertilizer, changes in water management to reduce the time when fields are flooded and the capture and use of manure CH_4 through anaerobic digesters (Graus et al., 2004; USEPA, 2006). A more detailed list of mitigation options is included in Table 9.

Table 9. Mitigation options for non-CO_2 emissions from agriculture (USEPA, 2006).

Affected gases	**Mitigation options**
Cropland N_2O and soil carbon	Less fertilization or split to smaller units
CH_4, N_2O and soil carbon from rice cultivation	Enhanced water management, such as full midseason drainage, shallow flooding, shift towards off-season straw to reduce availability of dissolved organic carbon, replacement of common fertilizers with ammonium sulphate, use of slow-release fertilizer, growing upland rice instead of paddy rice for less flooding
Livestock enteric fermentation	Improved feed conversion (e.g. increase the amount of grain), use of medical substances for faster weight gain, increasing milk production or reduced CH_4 production, feeding propionate precursors to reduce CH_4 production during digestion, intensive grazing for more nutritious pastures

Graus et al. (2004) identify considerable emission reduction options at relatively moderate costs. They assume the reduction potential for Western Europe to be around 13% below baseline in 2020 and around 36% below baseline in 2050; for Northern Africa, these values are –5% and –27%, respectively. Higher potentials may be available at higher costs.

For the global level, the U.S. EPA (2006) assumes a reduction potential of 10% below the baseline emissions at roughly zero costs on average over all gases by 2020. If very high costs of up to 120 euro/tCO_2-eq. are permitted, a reduction of 20% below baseline might be possible. The reduction potential varies between 1.5% and 17% for zero reduction costs and between 7% and 30% for costs of about 45 euro/tCO_2-eq. among Annex I countries and the relevant developing countries. However, due to methodological criteria, the U.S. EPA figures necessarily include the assumption that the cheapest measures are taken first and in their entirety. In addition, some of the measures could be controversial, such as the use of medical substances for faster weight gain.

This study's assumptions on reductions as provided in Table 5 (up to 50% reduction by 2050) are ambitious but not unrealistic in comparison to the reduction potentials identified in these studies.

3.3.6 Waste

Good reduction options exist for most emissions sources in the waste sector and include, among others, the covering of landfills or state-of-the-art wastewater reservoirs. Methane can be captured and used energetically (Höhne, 2005; Lucas et al., 2007). The assumption of substantial emission reductions to a fraction of today's emissions as made in this study is therefore realistic.

3.4 Quantitative results for all countries and discussion

This section includes the quantitative results on emissions that result from the *Triptych 7.0* calculations using the parameters given above.

Figure 9 shows the emissions and the emission reduction contributions of the different sectors on a global level under the three technology scenarios between 2000 and 2050 using the IMAGE 2.3 IPCC B2 emissions scenario as the baseline emissions.

The power-producing sector contributes by far the most to emission reductions, with reductions in this sector cumulating to about 200,000–350,000 GtC. Depending on the scenario, this is 15–25% of the overall cumulated baseline emissions between 2010 and 2100. The domestic and industry sectors follow, and together they show reductions of about the same amount as the power-producing sector, amounting to about 100,000–200,000 GtC, or about 5–15%, of the accumulated baseline emissions for each of the two sectors. The fossil fuel production, waste and agriculture sectors make only limited contributions to global emissions and, therefore, to emission reductions. The cumulated reduction of these sectors together accounts for about the same amount as the industry sector alone.

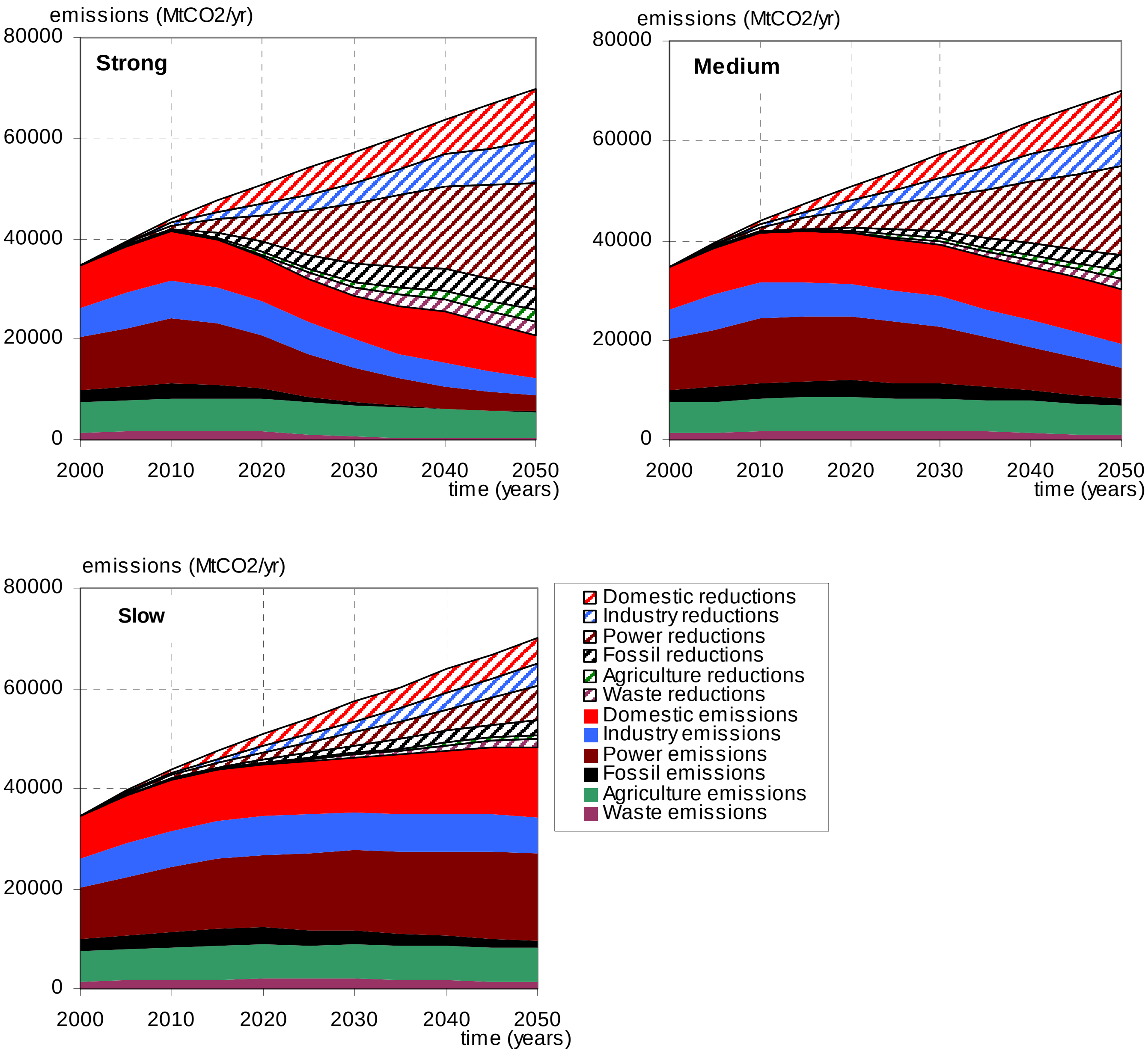

Figure 9 Global reduction contributions of the different sectors under the medium, slow and strong scenarios, respectively, between 2000 and 2050 using the IMAGE 2.3 IPCC B2 emissions scenario as the baseline emissions.

Figure 10 shows global emissions under the medium reduction scenario split by sectors on the global level. Most sectors reduce emissions after 2010/2020 more or less constantly. Emissions in the waste, agriculture and industry sectors behave quite similarly to each other in that they reduce about half of their emissions comparatively constantly between 2010 and 2050. Emissions in the industry sector decline faster between 2020 and 2050. In the power production sector, which is responsible for the highest share of emissions in 2010, even more stringent emission reductions are necessary between 2020 and 2060. The domestic sector is the only sector which increases emissions to peak and decline after 2050 in this case. By 2100, the power-producing sector contributes to about half of the total emission reductions (not shown here).

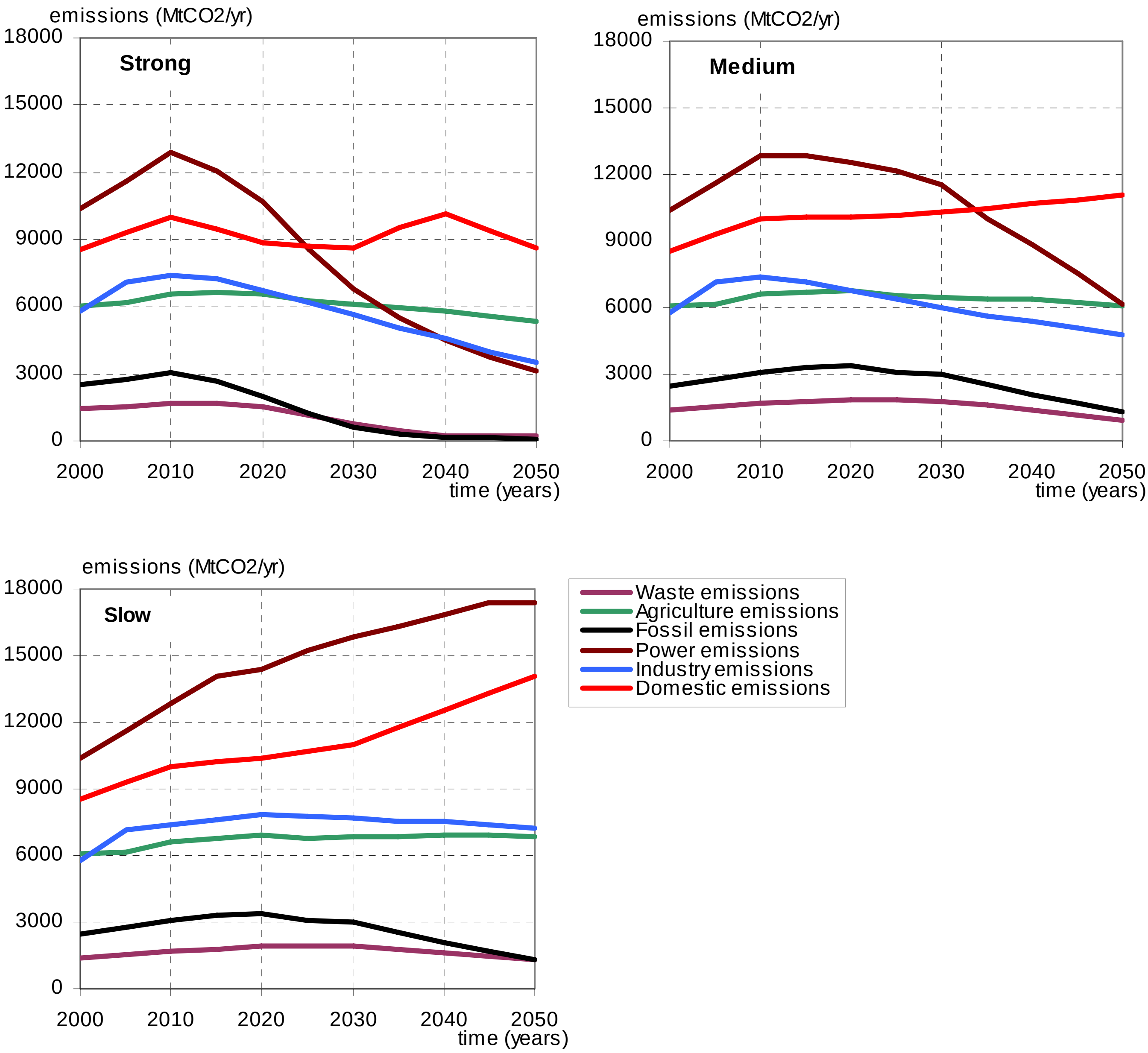

Figure 10 Overview of emission allowances for the different sectors at the global level for the slow, medium and strong reduction scenario between 2000 and 2050.

Table 10 compares the strong and medium scenario of this study with the sectoral emissions of the mitigation scenario aiming at stabilization at 450 and 550 ppm CO_2-eq., see Van Vuuren et al. (2006a). This table clearly shows that – on the global scale – the results are very similar and that the chosen Triptych parameters are compatible with technology scenarios from sophisticated models. In terms of the emissions from fossil production, agriculture and waste, the underlying reduction percentages are the same for both studies, both of which are based on Lucas et al. (2007). The emissions from the other sectors are also very close in both studies. The domestic sector emissions are similar, with both scenarios assuming very high reductions in this sector. However, on a country scale, rather large differences are evident between this study and that of Van Vuuren et al. (2000) – particularly in the domestic sector where a convergence in per capita domestic emissions is assumed; this leads to strong reductions in the OECD countries and excess emission allowances ('hot air') in the low-developing countries, such as India.

Table 10 Comparison of the sectoral emissions of the concentration stabilization scenarios of Van Vuuren et al. (2006a) and the strong and medium technology scenarios. Values in the table are given in GtC.

	Van Vuuren et al.		**This study**	
	450 ppm CO_2–eq.	550 ppm CO_2-eq.	Strong	Medium
Domestic	2.2	3.1	2.4	3.0
Industry	0.9	1.3	0.9	1.3
Power	0.5	1.7	0.8	1.7
Fossil	0.0	0.3	0.0	0.3
Agriculture	1.5	1.7	1.5	1.7
Waste	0.1	0.2	0.1	0.2
Total	5.2	8.3	5.7	8.3

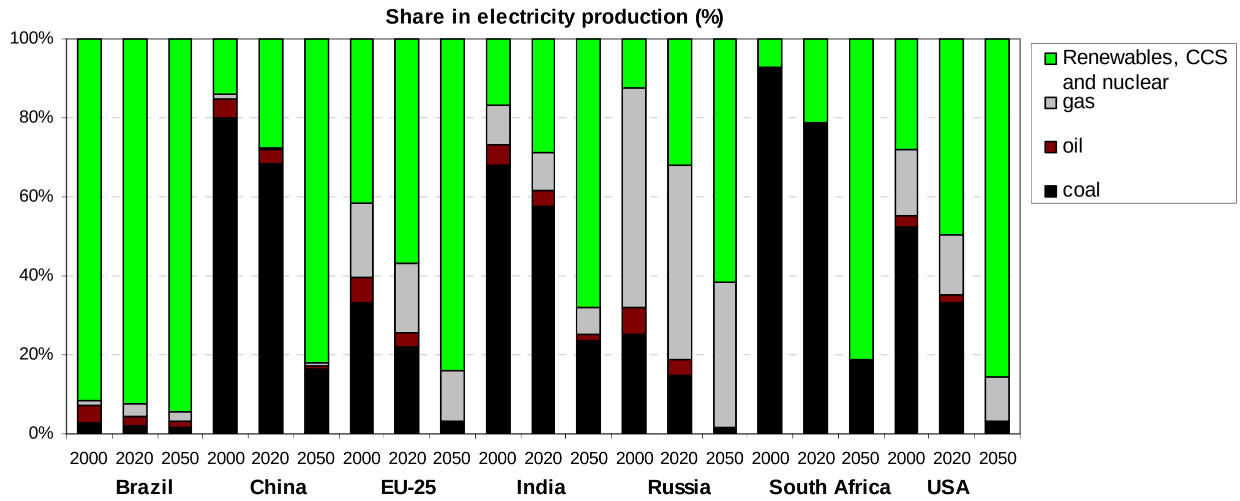

Figure 11 Overview of electricity production for the medium scenario for selected countries and the EU-25 region.

Figure 11 provides the electricity mix for 3 years (2000, 2020 and 2050) for Brazil, China, the EU-25, India, Russia, South Africa and the USA under the medium reduction scenario. Large differences can be seen in the electricity mix between countries, which result in different developments under the Triptych approach. Brazil currently has a very high share (~90%) of renewable energy; under the Triptych approach, this mix stays more or less constant over the years. Russia currently provides a high share of its electricity with natural gas (~60%); under the Triptych approach, this share remains constant, while it is mainly the use of coal that has to decrease and the renewable share to increase. South Africa currently produces approximately 90% of its electricity with coal, with nearly no use of other fossil sources; under the Triptych approach, the share of coal has to decrease considerably between 2020 and 2050 to slightly more than 30%. This allocation of coal is similar but a bit lower for China and India. The EU-25 and the USA have high shares of coal and emission-free sources in 2000; under the Triptych approach, the share of emission-free sources has to increase to about 75% by 2050, while the use of natural gas stays constant at about 20% over the years.

Figure 12 illustrates the emission allowances under the Triptych settings given above as percentage changes from 1990 emissions for selected countries and regions (see Appendix C for more detail). In this figure, the actual emissions in 1990 are compared with the amount of emission *allowances* for 2020 or 2050. It should be noted that *actual* emission levels may be different after emission trades have been applied. By 2020, it is the Annex I countries in particular which have to reduce their emissions substantially, although under the medium and strong convergence scenarios, Russia and the Middle East also have to contribute considerably. By 2050, the remaining Non-Annex I countries have to decrease its emissions significantly.

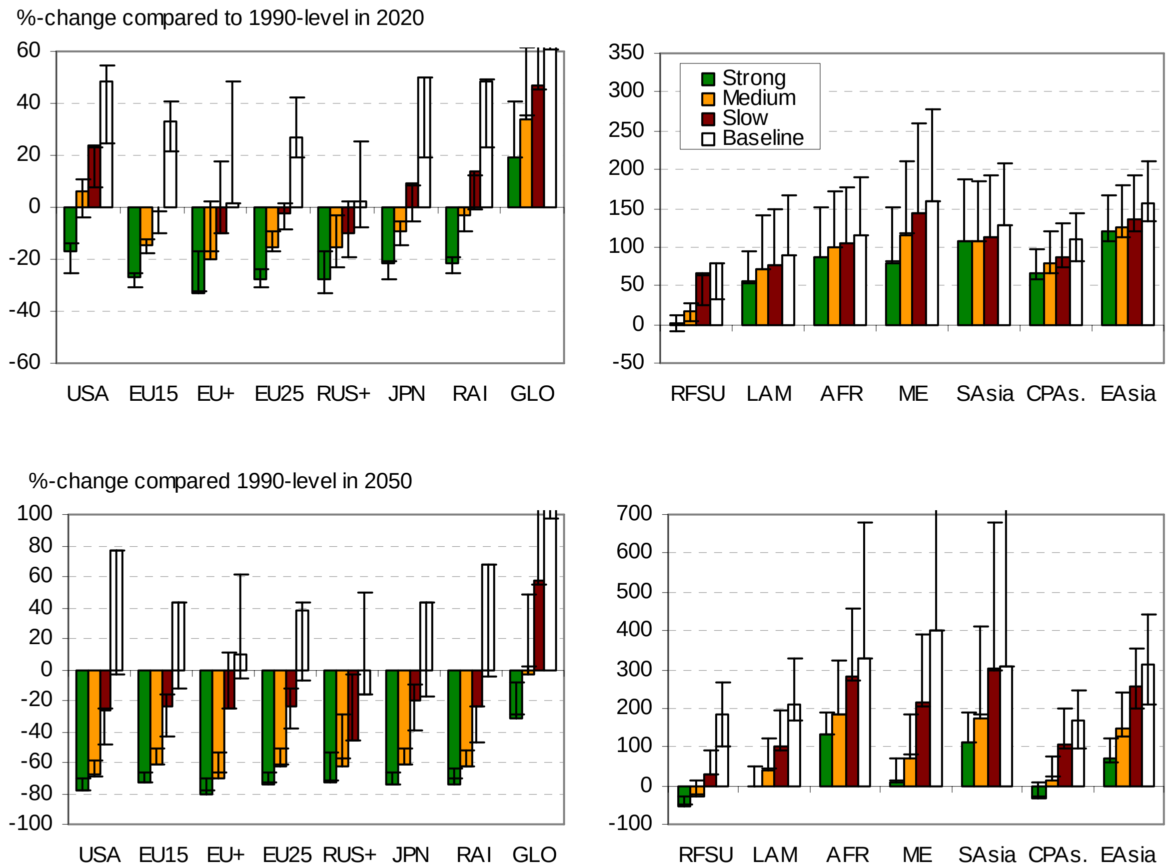

Figure 12 Change in emission allowances compared to 1990 levels in 2020 (upper) and 2050 (lower) for the country groups[12] under the three technology-oriented scenarios using the IMAGE B2 IPCC emissions scenario as the baseline emissions. The uncertainty range represents the outcomes under the highest and lowest IMAGE 2.3 IPCC scenarios.

Data similar to that presented in Figure 12 are used in Figure 13 to compare emissions with baseline emissions; that is, the same reductions are implemented, but these are compared to the

[12] EU+: new member states; RUS+: Russia and the rest of Europe in Annex I that are not members of the EU-25; JPN: Japan; RAI: Rest of Annex I; GLO: global; RFSU: Rest of former Soviet states; LAM: Latin America; AFR: Africa; ME: Middle East; SAsia: South Asia (essentially India); CPAs: centrally planned Asia (essentially China); EAsia: East Asia.

baseline level (and not to 1990 levels as in Figure 12). Under the strong scenario, most Annex I countries have to reduce emissions by about 30–55% below the baseline level; under the other scenarios, reductions are less stringent and amount to between 10 and 20% for most countries. Although Russia's 2020 allowances, when represented as change from 1990, are less stringent than those of other Annex I countries, Russia will have to reduce further below its baseline (–30% to –70%) than other Annex I countries. The reductions implemented by Non-Annex I countries lie between a 0 and –20% change from baseline. High emission regions, such as the Middle East (0 to –30% in 2020) and Russia (–5% to –40%) have lower reduction obligations.

By 2050, the reduction obligations compared to baseline for the Annex I countries are quite close for all Annex I countries and lie around –50% to –80%, depending on the scenario. Only the EU25 and Japan may reduce less (–20% to –50%) under the slow scenario. This advantage may be due to the current high efficiency in these countries.

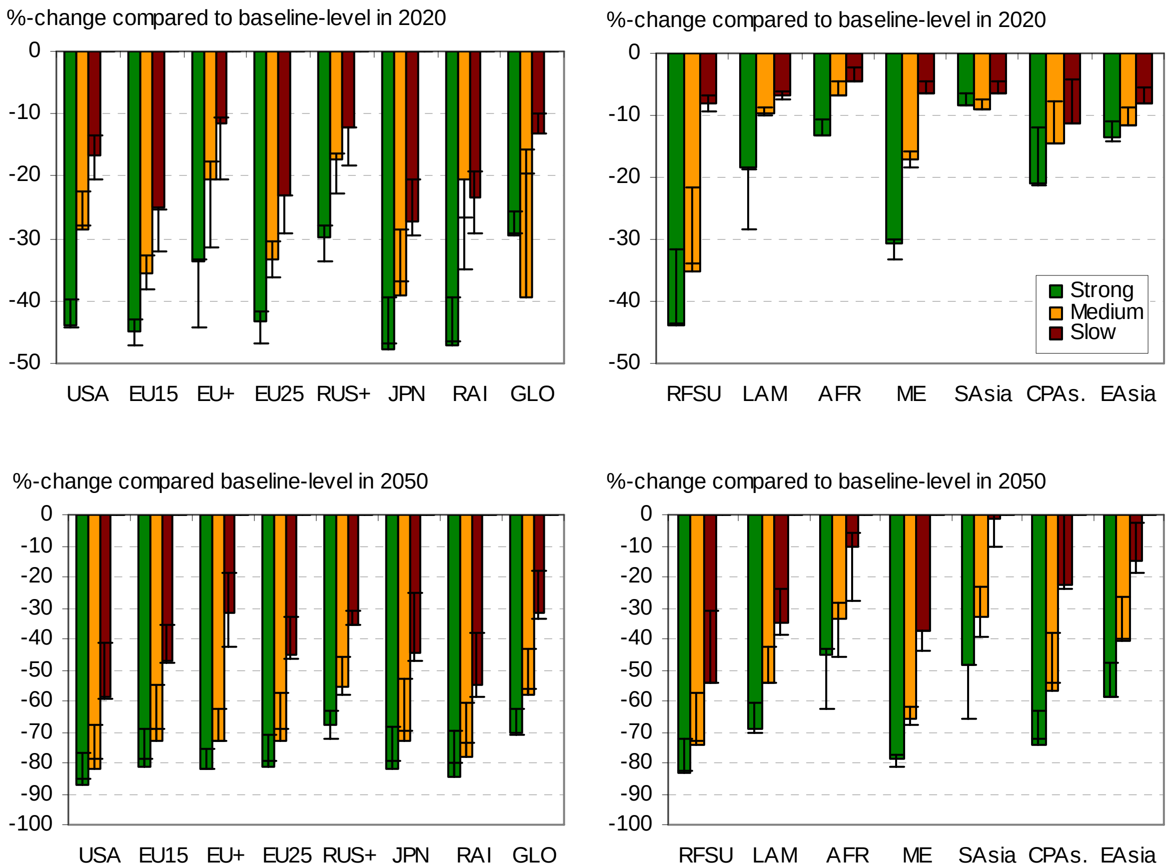

Figure 13 Change in emission allowances compared to baseline levels in 2020 (upper) and 2050 (lower) for the country groups under the three technology-oriented scenarios using the IMAGE 2.3 IPCC B2 emissions scenario as the baseline emissions. The uncertainty range represents the outcomes under the highest and lowest IMAGE 2.3 IPCC scenarios, respectively.

3.5 Discussion of the results per country

The following sections provide detailed descriptions of different countries, namely Brazil, China, the EU-25, India, Russia, South Africa and the USA, in terms of their future emission reduction contributions.

3.5.1 Brazil

Figure 14 presents the emissions and emission reduction contributions of the different sectors under the medium scenario between 2000 and 2100 for Brazil. Brazil has a particularly unique emission profile, with relatively low emissions in electricity production (due to the high availability of hydropower) and relatively high emissions from agriculture. No further reductions are necessary in the electricity sector, only growth is slowed. Agriculture emissions have to be reduced in the future, but emission reduction options in this sector are not readily available. Hence, the major contribution has to come from the domestic sectors, which will contribute the most to the emission reductions.

The strong scenario requires faster reductions (roughly 20% lower in 2050), and the slow scenario requires later reductions (roughly 10% higher in 2050). However, the general pattern over the sectors remains the same as that in the medium scenario.

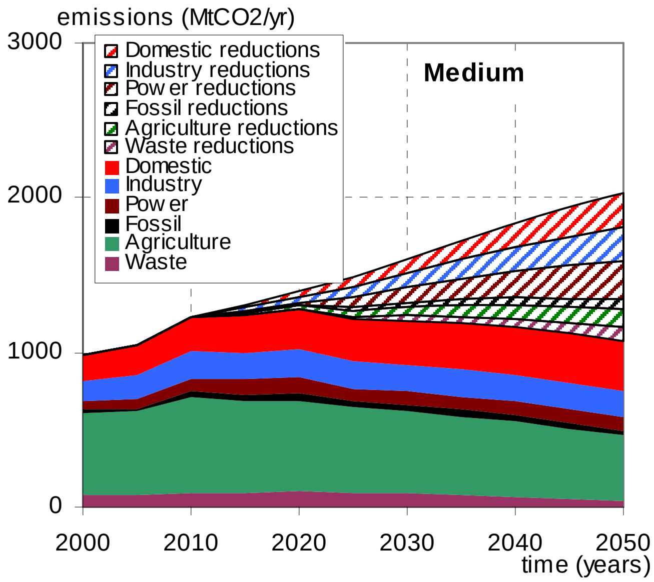

Figure 14 Reduction contributions of the different sectors under the medium scenario for Brazil between 2000 and 2050 using the IMAGE 2.3 IPCC B2 emissions scenario as the baseline emissions.

3.5.2 China

Figure 15 presents the emissions and emission reduction contributions of the different sectors under the medium scenario between 2000 and 2050 for China. China's emissions are dominated by those from the coal-intensive and fast-growing electricity sector, followed by those from the industrial and domestic sectors. Consequently, the Triptych approach requires significant reductions in the electricity sector in which not only growth is slowed, but emissions are also reduced in absolute terms. The share of coal in the electricity mix (without CCS) has to decrease from over 80% to less than 30% in 2050 in the medium scenario (Figure 11). Achieving this reduction will be a big challenge for China as not only the relative share of emission-free sources will increase but also the absolute need for energy will multiply. In addition, emissions from industry would have to decline in absolute terms, as there is a large potential to improve the energy efficiency in this sector (by a factor of 2, as the EEI assumed here is 1.9). Reductions by the domestic sector are not significant, as per capita emissions in this area are very small. Of the remaining sectors, agriculture is significant mainly due to rice production and also has to contribute to the reduction effort.

The strong scenario requires faster reductions in the short term (roughly 20% lower in 2030), and the slow scenario requires later reductions (roughly 30% higher in 2050). However, the general pattern over the sectors remains the same as that in the medium scenario.

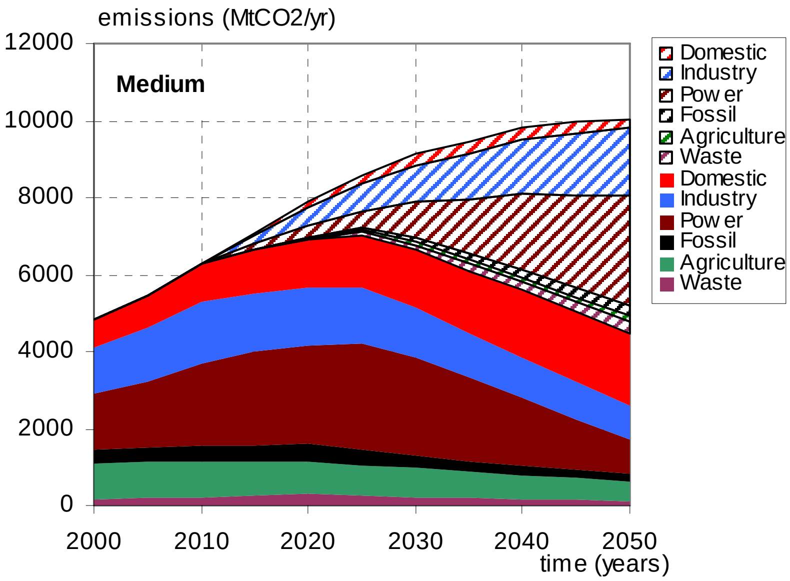

Figure 15 Reduction contributions of the different sectors under the medium scenario for China between 2000 and 2050 using the IMAGE 2.3 IPCC B2 emissions scenario as the baseline emissions.

3.5.3 EU-25

Figure 16 presents the emissions and emission reduction contributions of the different sectors under the medium scenario between 2000 and 2050 for the EU-25. Current emissions are split roughly evenly between the domestic, industry and electricity sectors, with the other sectors contributing only to a minor extent. As industry is seen to be efficient in EU-25 countries, minimal reductions are expected from that sector under the Triptych approach; however, major reductions (absolute and below baseline) are required from the electricity and the domestic sectors. The share of coal in the electricity mix (without CCS) has to decline from 30% to 5%. The high per capita emissions in the domestic sector require significant reductions to a very low level in 2050.

The strong scenario requires faster reductions (roughly 20% lower in 2050), and the slow scenario requires later reductions (roughly 30% higher in 2050). However, the general pattern over the sectors remains the same as that in the medium scenario.

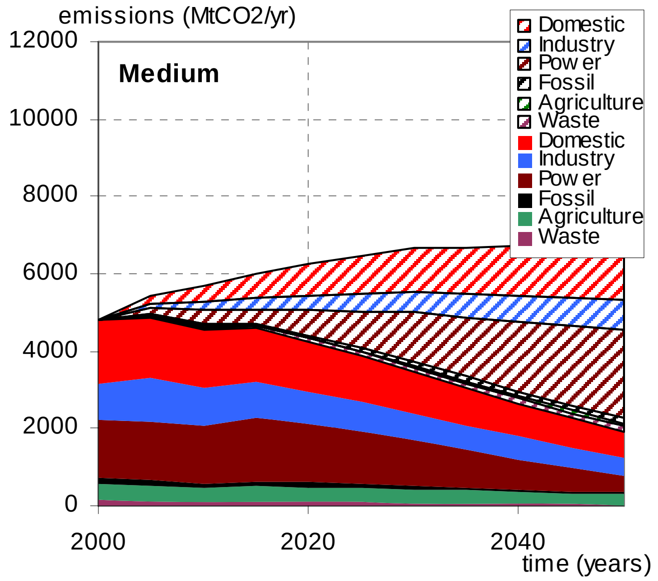

Figure 16 Reduction contributions of the different sectors under the medium scenario for the EU-25 between 2000 and 2050 using the IMAGE 2.3 IPCC B2 emissions scenario as the baseline emissions.

3.5.4 India

Figure 17 presents the emissions and emission reduction contributions of the different sectors under the medium scenario between 2000 and 2050 for India. India's current emissions are dominated by the power sector. Due to a high share of coal in electricity production, emissions in this sector are required to be reduced. Present-day per capita emissions in the domestic sector are very low today, but emissions are assumed to increase, both on a per capita level as well as on the country level, as the population increases. Emissions from transport in particular can be assumed to make up for an increasing share of future domestic emissions. Because of the low starting point, emissions are allowed to increase above the reference development (sometimes called 'hot air'), but on the national total level, emissions are not allowed to increase above the baseline development. Of the remaining sectors, emissions from agriculture are significant mainly due to rice cultivation as well as animal husbandry and have to contribute to the reduction effort.

The strong scenario requires faster reductions (roughly 10% lower in 2050), and the slow scenario requires later reductions (roughly 20% higher in 2050). However, the general pattern over the sectors remains the same as that in the medium scenario.

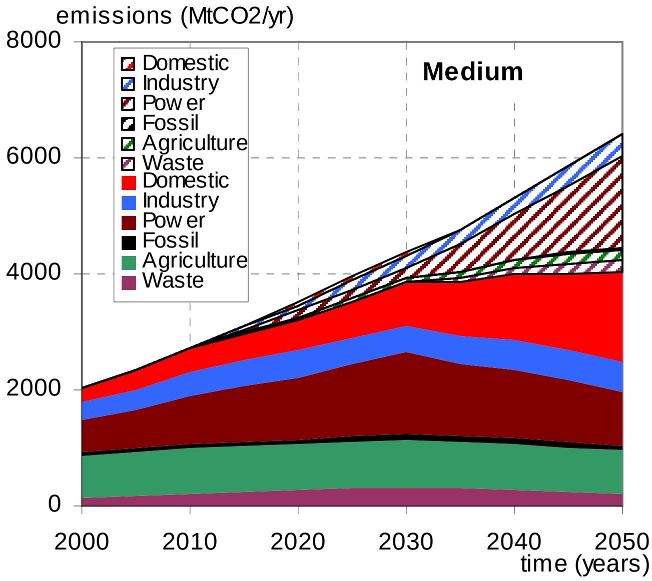

Figure 17 Reduction contributions of the different sectors under the medium scenario for India between 2000 and 2050 using the IMAGE 2.3 IPCC B2 emissions scenario as the baseline emissions. (Emissions in the domestic sector are allowed to increase above the reference until 2080 and are not indicated as reduction below reference).

3.5.5 Russia

Figure 18 presents the emissions and emission reduction contributions of the different sectors under the medium scenario between 2000 and 2050 for Russia. Russia's emissions are dominated by the electricity sector, which is based mainly on gas and coal. Consequently, the Triptych approach requires significant reductions in this sector. Similar to other Annex I countries and high-emission countries, the share of fossil sources in the electricity mix will have to decrease considerably by 2050 in the medium scenario (Figure 11). While the share of gas can stay constant, oil and coal will have to be reduced in order to contribute even only a few percentage points to the electricity production in 2050. In addition, reductions in the domestic sector are significant, as per capita emissions in this area are high. Emissions from industry would have to decline in absolute terms, as there is high potential to improve the energy efficiency in the industry sector as the EEI assumed for Russia is 2.5. The emissions from fossil fuel production are particularly high, with one example being those from leaking gas pipelines. While it will be necessary to reduce these emissions to a very low level in terms of emission reduction contributions, the economic aspect of these emissions is also of great significance. As national total emissions are expected to decline considerably even under the reference scenario, the overall reductions should be achievable for Russia.

The strong scenario requires faster reductions in the short term (roughly 15% lower in 2050), and the slow scenario requires later reductions (roughly 10% higher in 2050), but the general pattern over the sectors remains the same as that in the medium scenario.

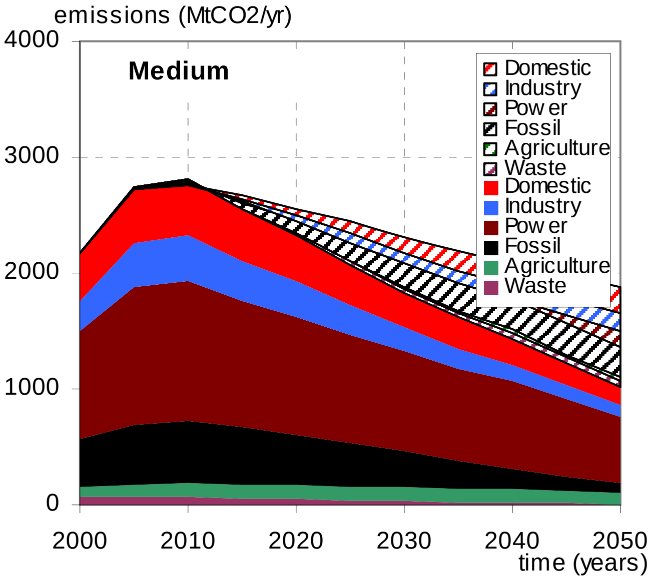

Figure 18 Reduction contributions of the different sectors under the medium scenario for Russia between 2000 and 2050 using the IMAGE 2.3 IPCC B2 emissions scenario as the baseline emissions.

3.5.6 South Africa

Figure 19 presents the emissions and emission reduction contributions of the different sectors under the medium scenario between 2000 and 2050 for South Africa. Similar to China, South Africa's emissions are dominated by the coal-intensive and fast-growing electricity sector, followed by fugitive emissions from coal production and then industrial and domestic emissions. Consequently, the Triptych approach requires significant reductions in the electricity sector, not only in terms of slowing growth but also of reducing emissions in absolute terms. The share of coal (without CCS) in the electricity mix has to decrease from over 80% to less than 30% in 2050 in the medium scenario (Figure 11). This will be a major challenge for South Africa as not only the relative share of emission-free sources will increase but also the absolute need for energy will multiply as the country develops further. In addition, emission from industry would have to decline in absolute terms, as there is a high potential to improve the energy efficiency in the industry as the EEI is assumed to be 2.5. Reductions in the domestic sector are also significant, as per capita emissions in this area are already high.

The strong scenario requires faster reductions in the short term (roughly 40% lower in 2050), and the slow scenario requires later reductions (roughly 40% higher in 2050). However, the general pattern over the sectors remains the same as that in the medium scenario.

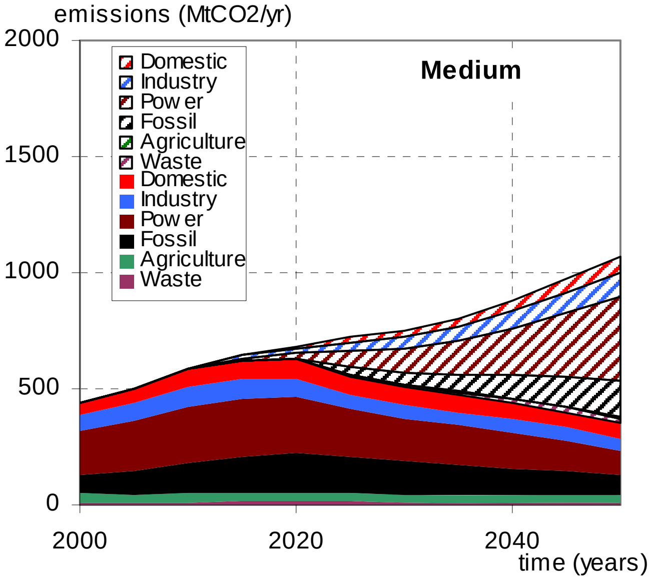

Figure 19 Reduction contributions of the different sectors under the medium scenario for South Africa between 2000 and 2050 using the IMAGE 2.3 IPCC B2 emissions scenario as the baseline emissions.

3.5.7 USA

Figure 20 presents the emissions and emission reduction contributions of the different sectors under the medium scenario between 2000 and 2050 for the USA. The U.S. emissions are dominated by the fossil fuel-intensive electricity sector, followed by a very high share of domestic emissions. Consequently, the Triptych approach requires significant absolute reductions in the electricity sector. The share of coal (without CCS) in the electricity mix has to decrease from over 80% to less than 30% in 2050 in the medium scenario (Figure 11). In addition, emission from domestic sector, especially from transport, will have to decline in both absolute and per capita terms. Emissions from the industry sector also provide a reduction potential as the EEI assumed here is 1.6, but the potential is this sector is much less than that in the power sector and domestic sectors.

The strong scenario requires faster reductions in the short term (roughly 30% lower in 2050), and the slow scenario requires later reductions (roughly 60% higher in 2050). However, the general pattern over the sectors remains the same as that in the medium scenario.

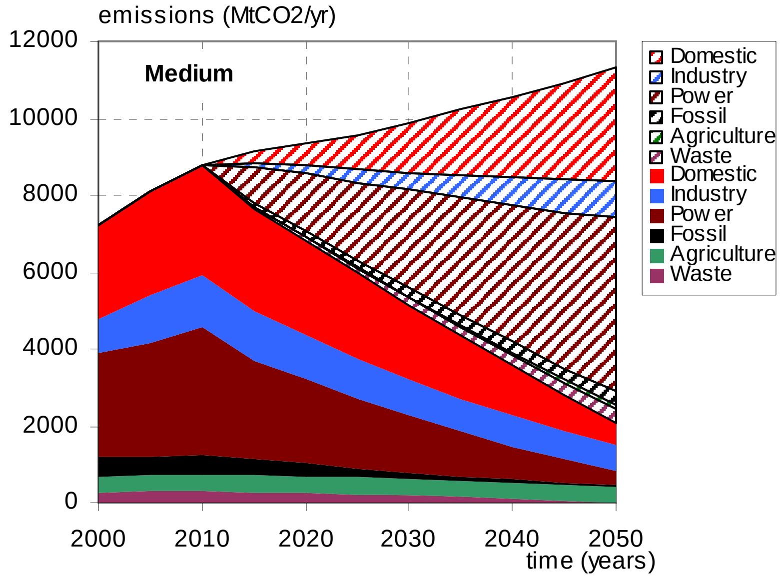

Figure 20 Reduction contributions of the different sectors under the medium scenario for the USA between 2000 and 2050 using the IMAGE 2.3 IPCC B2 emissions scenario as the baseline emissions.

4 Discussion and conclusions

The Triptych approach is a method which has been developed to differentiate emission reduction requirements under a future international climate agreement among countries based on technological considerations on the sector level. It defines criteria and rules for differentiating future commitments for all regions in a consistent and transparent manner. The advantage of the Triptych approach is that emission allowances are decomposed according to sectors, thereby enabling the link to real-world emission reduction strategies to be more concrete than has been possible to date. Its framework also allows for discussions on sectors that compete worldwide and, in a natural way, on the role of developing countries in making contributions to emission limitation and reduction targets. The major downside of the approach, however, remains its complexity and the necessity for projections of production growth rates.

The Differentiated Convergence Triptych 7.0 presented in this report builds on an earlier version of the Triptych approach by refining the methodology to improve the transparency (simplified methodology for the electricity sector) and to accommodate the tendency of developing countries to act only after industrialized countries have acted (initial participation of developing countries with incentives but no penalties through ‘no-lose’ targets or SD-PAMs.

The approach has been implemented using a policy-support tool, the FAIR model, and the implications of the approach on the emission allowances of various countries are presented for three sets of Triptych parameters – the slow, medium and strong scenario, respectively (see Table 11). The strong scenario is compatible with a stabilization of GHG concentrations at 450 ppm CO_2-eq., and the medium scenario with a stabilization of GHGs concentrations at 550 ppm CO_2-eq. The reductions in Table 11 may sound very ambitious and (at first sight) politically unacceptable, but this study also shows that these are achievable in the short term with currently available technology and in the long term with very likely available technological options. This study did not consider explicitly the costs (and benefits) of reducing emissions, but the fact that these technologies are available indicate that total costs will not be extremely high.

Table 11. Summary of the required reductions under *Triptych 7.0* for the strong, medium and slow scenarios, respectively.

	2020		**2050**	
	Relative to 1990 (%)	**Relative to Baseline (%)**	**Relative to 1990 (%)**	**Relative to Baseline (%)**
Strong (450 ppm CO_2-eq.)				
Annex I countries	-23	-42	-75	-83
Non-Annex I countries	73	-19	25	-64
World	19	-29	-32	-70
Medium (550 ppm CO_2-eq.)				
Annex I countries	-6	-30	-65	-75
Non-Annex I countries	86	-13	76	-49
World	34	-21	-4	-58
Slow				
Annex I countries	8	-19	-29	-51
Non-Annex I countries	97	-8	171	-22
World	47	-13	58	-32

The modelling also clearly demonstrates that the very different emission profiles of countries can be considered in both an explicit and differentiated manner using the Triptych approach. The emission profile of Brazil (dominated by agriculture) and China (dominated by coal) are very different and, consequently, the reduction requirements are different, as the Triptych methodology applies different rules for the different sectors.

The major advantage of the Triptych approach is that its emission targets are largely compatible with the existing technical emission reduction potentials in the various countries as growth is allowed but efficiency has to be improved (see also Table 12). An additional degree of cost-effectiveness is provided through the introduction of emissions trading into the model. Although the Triptych approach is based on sector-specific considerations, a national target has been provided instead of several sectoral targets, and this national target provides countries with a degree of flexibility to pursue cost-effective emission reduction strategies. Parties can reduce emissions across sectors and, if emission trading and CDM is allowed, also outside of their territory.

Structural differences, such as differences in the standard of living, in future population growth, in the fuel mix for power generation, in the economic structure, in energy efficiencies and in projected future changes in economic structure, are taken explicitly into account at a sector level. The emissions of all GHGs are also considered; as a result all of the major emission sectors of developing and developed countries are covered.

The Triptych approach also puts internationally competitive industries on the same level as the same rules apply to these industries in all countries.

The approach has also already been applied successfully on the EU level as a basis for negotiating targets.

The major disadvantage of the Triptych approach is that it is relatively complex compared with a number of other approaches. Nevertheless, the concept of the Triptych approach can be easily explained. Countries have to agree on the Triptych parameters being applicable to all countries, such as the convergence level of the domestic sectors and changes in the fuel mix for electricity generation. Further, the approach requires a set of scenarios, including the expected growth rates of production in the various sectors, which can be provided by the countries themselves. There is, however, an incentive to provide high-growth scenarios. This problem could be overcome by making adjustments after the commitment period, if the projected growth rate turns out to be considerably higher than the actual one, or by using the actual production growth rate. Once the targets are defined, the requirements in terms of verification of the implementation of the targets are the same as those for the Kyoto Protocol. Overall, the implementation of the approach remains rather complex, which becomes particularly problematic if applied to (the least) developing countries.

Table 12. Summary of strengths and weaknesses of Triptych 7.0.

Strengths	Weaknesses
▪ Emission reductions are directly related to technical emission reduction potentials ▪ National circumstances are explicitly accommodated ▪ Explicitly allows for economic growth at improving efficiency in all countries ▪ Aims to put internationally competitive industries on same level ▪ Has been successfully been applied (on EU level) as a basis for negotiating targets ▪ Compatible with Kyoto Protocol (reporting and mechanisms) ▪ New version allows delayed developing country participation	▪ High complexity of the approach requires many decisions and sectoral data, making global application a challenge, and it may be perceived as not being transparent ▪ Agreement on required projections of production growth rates for heavy industry and electricity may be difficult

A concluding question is: *Can the Triptych 7.0 approach be a starting point for a future international climate agreement?*

The Triptych 7.0 approach described here takes into account the major basic principles of international climate policy as laid down in the Climate Convention, thereby making it more acceptable to many countries. These include:

1. The notion of equity and the ‘common but differentiated responsibilities’;
2. The specific needs and special circumstances of developing countries, thereby allowing economic growth;
3. Cost-effectiveness of measures;
4. Harmonization of climate change mitigation measures and sustainable development.

Any approach will have to face objections from one side or the other – or, possibly, from both sides. The approach that will have a chance of being acceptable to all parties will have to face criticism and objections on its component elements from all sides and be able to satisfy these in a balanced manner, not giving one side an advantage over the other. In other words, all sides have to be ‘equally unhappy’ with the approach. The objective of this report was to refine the rules of *Triptych 7.0* so that this is the case.

The combination of the convergence of per capita emissions in the domestic sectors with a flexibility for growing production with increasing efficiency (in industry and electricity) and the fact that structural differences are taken into account could be attractive to many countries as a compromise solution and, thereby, could help in building trust. Most developing countries have clearly indicated their preference for the convergence of per capita emissions in the long term. However, some developed countries are strictly opposed to the concept of per capita emissions. Triptych is a compromise. The various parameters and accounting for structural differences leaves room for negotiations.

Triptych 7.0 may be appealing to *developing* countries since growth can still occur (in electricity and industrial production), but efficiency has to be improved. The approach does not cap economic growth, but supports development in a sustainable manner. The new element of delayed participation of developing countries may make the approach further appealing to developing countries.

Triptych 7.0 may also be appealing to *developed* countries as it gives a clear indication when and how developing countries participate and it is based on the obligation of developing states to reduce emissions according to the same sectoral rules as developed countries. It is particularly appealing to those countries that are already very efficient.

We believe that even if the Triptych approach is not used as an officially recognized tool in its entirety during future negotiations, its elements constitute a useful input into such discussions and may eventually find an application in a definitive international climate agreement.

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Appendix A Characterization of the Triptych versions

Table A.1 Characterization of the earlier Triptych versions and the new Triptych 7.0 version (adapted from Höhne et al., 2005). Bold indicate changes compared to *Triptych 6.0.*

Sector	***Original Triptych*** **(Blok et al., 1997)**	***Global Convergence Triptych*** **(Groenenberg, 2002)**	***Extended Global Triptych*** **(Höhne et al., 2003)**	***Triptych 6.0*** **(Höhne et al., 2005)**	***Triptych 7.0*** **(this study)**
General					
Target year	2010	2020	2020	2000 to 2050	2000–2050
Base-year	1990	1995	1990	1990, 2000, 2010	1990, 2000, 2010
Gases	Energy-related CO_2	CO_2, CH_4, N_2O, and PFCs	CO_2, CH_4, and N_2O	CO_2, CH_4, N_2O, HFCs (sum), PFCs (sum) and SF_6	CO_2, CH_4, N_2O, HFCs (sum), PFCs (sum) and SF_6
Countries	EU Member States	Applied to global level (13 regions and 48 countries)	Applied to global level (48 countries)	Up to 192 (dependent on data availability)	**224 (dependent on data availability)**
Target	–9 to –17%	450/550 CO_2/CO_2-eq. and 550/650 CO_2/CO_2-eq. profiles	450/550 ppm CO_2	450/550 ppm CO_2	450/550ppm CO_2-eq.
Internationally Operating Energy-Intensive Industries:					
Source	Capros et al. (1995) data	IEA data	IEA data	UNFCCC/ IEA data	**IEA and EDGAR data**
Growth rate	Based on CW scenario: 1) Differentiated: 2.1%/year in Cohesion Fund countries, 1.1%/year in others 2) 1.2%/year for all countries as of the base year	Total growth modelled as a function of population growth, economic growth and growth rates of per capita production based over five income categories. Average projections for	• According to WEC, 1995: 1.1% for EU, 1.0% for OECD, 0.5% for Eastern Europe/Russia, 3.9% for developing countries • CH_4 and N_2O assumed proportional to CO_2 emissions from energy	• Choice of using the normative growth rates or the reference growth rates. • Downscaling to countries using the regional trend • Maximum deviation of normative growth rate from scenario	• **Energy consumption in the industry sector from IMAGE IPCC SRES scenarios** • **Improved downscaling methodology to countries**

Sector	***Original Triptych*** **(Blok et al., 1997)**	***Global Convergence Triptych*** **(Groenenberg, 2002)**	***Extended Global Triptych*** **(Höhne et al., 2003)**	***Triptych 6.0*** **(Höhne et al., 2005)**	***Triptych 7.0*** **(this study)**
		per capita production Growth from IPCC SRES (2000)[13]		value • Industrial Value Added (IVA) for regions of the IMAGE 2.2 scenarios • As IVA grows faster than industrial production, caused by shift in economic structure to higher VA sectors over time. A structural change factor is applied to account for this	
Energy efficiency	• 1.5% reduction of SEC (GJ/t) per year for all countries • Differences in energy efficiency not taken into account	• Convergence of regional energy efficiency by convergence year. • Developing countries improve with 1%/year until 2010 before converging. • Initial EEI for regions (taken from Groenenberg, (2002)	• 1.5% per year reduction of specific CO_2 emissions (Mt CO_2/t) for all countries • Differences in energy efficiency not taken into account	• Convergence of regional energy efficiency by convergence year. • Initial EEI for regions (taken from Groenenberg, (2002)	• **Convergence of regional energy efficiency by convergence year** • **Developing countries improve with 1%/year until 2010 before converging** • **Initial energy efficiency index for countries, from new calculations this study**
Decarbon-ization	Decarbonization of fuels, 0.17% per year	No decarbonization – included in CO_2 emission improvement rate	No decarbonization – included in CO_2 emission improvement rate	No decarbonization – included in CO_2 emission improvement rate	No decarbonization – included in CO_2 emission improvement rate
Sectors	Iron and steel, petrochemical industry, ammonia, primary aluminium, cement, pulp and paper	Energy and process emissions of iron and steel, petrochemical industry, ammonia, primary aluminium,	Energy and process emissions of iron & steel, petrochemical industry, ammonia, primary aluminium, cement, pulp and	Energy and process emissions of iron and steel, petrochemical industry, ammonia, primary	Energy and process emissions of iron and steel, petrochemical industry, ammonia, primary

[13] In the FAIR 2.0 implementation, the population and economic growth scenarios are based on the IMAGE implementation of the IPCC SRES scenarios.

Sector	***Original Triptych*** **(Blok et al., 1997)**	***Global Convergence Triptych*** **(Groenenberg, 2002)**	***Extended Global Triptych*** **(Höhne et al., 2003)**	***Triptych 6.0*** **(Höhne et al., 2005)**	***Triptych 7.0*** **(this study)**
		cement, pulp and paper	paper	aluminium, cement, pulp and Paper	aluminium, cement, pulp and paper
Domestic Sector					
Population	Growth based on European Community	Growth based primarily on Lutz et al. (1996) as well as UN forecasts[14]	Growth based on UN forecasts	Growth based on regional downscaling of IMAGE 2.2 scenarios, using initial UN data	**Country-specific population scenarios**
Convergence year	2030	2050	2030	2050	2050
Convergence level	2.96 t/capita	2.0 t/capita	3.0 t/capita		
Climate correction	Used	Not used	Not used	Not used	Not used
Sectors	Households, services, light industry, agriculture and transportation	Households, services, light industry, agriculture and transportation	Households, services, agriculture and transportation	Households, services, agriculture and transportation	Households, services, agriculture and transportation
Power Sector					
Electricity production growth	1.9%/year for Cohesion Fund countries (Greece, Ireland, Portugal and Spain); 0.9%/year non-Cohesion Fund countries: (average equal to CW scenario)	Growth determined as the weighted sum of growth in total final energy consumption in the energy-intensive industry and domestic sectors.	Based on economic growth rates differentiated over 11 world regions less 1% to compensate for autonomous energy improvements	• Electricity demand, per capita GDP, derived from IMAGE scenarios (regional downscaling) • Current efficiencies/emission factors per fossil fuel type (from IEA 2002) The growth rates used are normative but scenario derived.	

[14] In the FAIR 2.0 implementation, the population scenarios are based on the IMAGE implementation of the IPCC SRES scenarios

Sector	***Original Triptych* (Blok et al., 1997)**	***Global Convergence Triptych* (Groenenberg, 2002)**	***Extended Global Triptych* (Höhne et al., 2003)**	***Triptych 6.0* (Höhne et al., 2005)**	***Triptych 7.0* (this study)**
Solids	70% of 1990 levels (Denmark, 35%; Germany, 50%; UK, 35%)	GHG intensity convergence at 200g CO_{2e}/kWh. Convergence based on renewables having a share of 60% of electricity generated in 2050 with equal remaining shares of oil, coal and gas. Developing countries do not participate until 2010.	70% of 1990 levels	70% of 1990 levels	
Liquids	70% of 1990 levels (Denmark, 35%; Germany, 50%; UK, 35%)		70% of 1990 levels	70% of 1990 levels	
Renewables	1990 levels plus 8%		20% share of 2020 electricity production	20% share of 2020 electricity production	
CHP	15% of 2010		30% share of 2020 electricity production	30% share of 2020 electricity production	
Nuclear	Nuclear power based on CW scenario		Nuclear production in 2020 equals 1990 production levels	Nuclear production in 2020 equals 1990 production levels	
Efficiency	From CW scenario	Generating efficiencies converge in 2030 for solid/liquid fuels (45% efficiency), natural gas (60%), CHP (70%)	Generating efficiencies converge in 2030 for solid/liquid fuels (45% efficiency), natural gas (60%), CHP (70%)	Generating efficiencies converge in 2030 for solid/liquid fuels (45% efficiency), natural gas (60%), CHP (70%)	Generating efficiencies converge in 2030 for solid/liquid fuels (45% efficiency), natural gas (60%), CHP (70%)
Fossil fuel production	Not included	CH_4 emissions/unit fossil fuel production reduced to 90% by 2050 (fossil fuel production assumed proportional to CO_2 emissions from fossil fuel combustion)	CH_4 emissions directly proportional to changes in CO_2 emissions from fossil fuel combustion	Reduce emissions by *x*% in target year	Reduce emissions by *x*% in target year

Sector	***Original Triptych* (Blok et al., 1997)**	***Global Convergence Triptych* (Groenenberg, 2002)**	***Extended Global Triptych* (Höhne et al., 2003)**	***Triptych 6.0* (Höhne et al., 2005)**	***Triptych 7.0* (this study)**
Agriculture	Not included	Stabilization of CH_4 and N_2O at 1990 levels[15]	Stabilization of CH_4 and N_2O to be at 1990 levels	Reduction percentages compared to reference scenario in various years for two groups of countries	Reduction percentages compared to reference scenario in various years for two groups of countries
Deforestation	Not included	Per capita emissions from deforestation is assumed to converge to 0 in 2050	Per capita emissions from deforestation is assumed to converge to 0 in 2050	Per capita emissions from deforestation is assumed to converge to 0 in 2050	Per capita emissions from deforestation is assumed to converge to 0 in 2050 (these emissions were excluded in this report)
Waste	Not included	Not included	Included in domestic sectors	Linear convergence of per capita emissions to *x* tCO_2-eq/cap	Linear convergence of per capita emissions to *x* tCO_2-eq/cap

[15] In FAIR 2.0, we assume these emissions are linearly reduced by 35% compared to baseline emissions between 2020 and 2040.

Appendix B Energy Efficiency Index (EEI)

The EEI is used as the energy efficiency indicator. The calculation of Energy Efficiency Indices (EEI) follows the method applied in several previous studies (Groenenberg et al., 2004; Phylipsen et al., 1998; Price et al., 2001; Worrell et al., 1994; 1997). A value for specific energy consumption (SEC) can be calculated as:

$$SEC = \frac{E_{tot}}{P_{tot}} = \frac{\sum_{i=1}^{n} (p_i * SEC_i)}{\sum_{i=1}^{n} p_i} \tag{B.1}$$

in which E_{tot} is the total energy consumption in the subsector, P_{tot} is the total production in the subsector, SEC_i is the specific energy consumption for product *I*, p_i is the physical production level of product *i* and *n* is the number of products.

A reference value for the SEC is indispensable to evaluate the energy consumption in a country's industry. Similarly, the reference SEC in a subsector can be defined as:

$$SEC_{ref} = \frac{E_{ref,tot}}{P_{tot}} = \frac{\sum_{i=1}^{n} (p_i * SEC_{ref,i})}{\sum_{i=1}^{n} p_i} \tag{B.2}$$

in which: $E_{ref,tot}$ is the reference level for total energy consumption in the subsector.

The EEI in a subsector in a country is calculated as:

$$EEI = \frac{E_{tot}}{E_{ref,tot}} = \frac{\sum_{i=1}^{n} p_i * SEC_i}{\sum_{i=1}^{n} p_i * refSEC_i} \tag{B.3}$$

This method enables the various products produced with specific process and energy requirements in a specific industrial subsector to be taken into account. An EEI equal to 1 indicates that the actual SEC is at the reference level, while a lower EEI means a higher level of energy efficiency. The EEI may be aggregated over various subsectors and countries using the same formulas (B.2) and (B.3). The SEC are studied in terms of primary energy. For the calculation of energy intensities in the energy-intensive industry in *Global Convergence Triptych*, a 40% fuel-to-electricity standard efficiency conversion rate is applied for all countries. This value is proposed by Phylipsen et al. (1998), based on a fact that the public electricity generation efficiency of most countries is between 35% and 45%. The application of the uniformed conversion factor for all countries for electricity generation enables changes and differences to be highlighted in subsectoral energy intensities in the iron and steel industry and not the efficiency of public electricity production of a country (Groenenberg et al., 2004; Worrell et al., 1997).

Appendix C Emission allowance data under all scenarios

Table B.1 The emission allowances of countries or aggregated groups of countries under the Strong Technology scenario.

	1990	2020				2050			
450 ppm	**1990**	**Baseline**	**Target**	**Relative to 1990**	**Relative baseline**	**Baseline**	**Target**	**Relative to 1990**	**Relative baseline**
	$MtCO_2$-eq	**$MtCO_2$-eq**	**$MtCO_2$-eq**	**%**	**%**	**$MtCO_2$-eq**	**$MtCO_2$-eq**	**%**	**%**
Annex I countries	17282	23021	13308	-23	-42	24864	4255	-75	-83
Non-Annex I countries	13295	28532	23050	73	-19	45847	16653	25	-64
World	30577	51553	36358	19	-29	70711	20907	-32	-70
01 USA	6361	9452	5289	-17	-44	11262	1418	-78	-87
02 EU-15	4101	5454	3004	-27	-45	5898	1090	-73	-82
03 EU-10	906	917	607	-33	-34	990	180	-80	-82
04 Rest of Western Europe	104	148	78	-26	-48	155	33	-69	-79
05 Russia	2834	2607	1933	-32	-26	2017	697	-75	-65
06 Rest of Eastern Europe in Annex I countries	623	935	559	-10	-40	882	236	-62	-73
07 Japan	1214	1819	949	-22	-48	1742	311	-74	-82
08 Rest of Annex I countries	1148	1705	902	-21	-47	1940	297	-74	-85
09 Turkey	221	418	333	50	-20	713	270	22	-62
10 Rest of Eastern Europe	941	1712	869	-8	-49	2564	305	-68	-88
11 Argentina	260	432	333	28	-23	670	203	-22	-70
12 Brazil	751	1435	1167	55	-19	2187	765	2	-65
13 Mexico	484	906	702	45	-22	1464	384	-21	-74
14 Venezuela	174	391	363	108	-7	706	146	-16	-79
15 Rest of Latin America	568	1079	900	58	-17	1883	644	13	-66
16 Egypt	131	349	310	137	-11	615	291	122	-53
17 South Africa	396	669	451	14	-32	1112	136	-66	-88
18 Nigeria	126	330	309	146	-6	744	438	248	-41
19 Rest of North Africa	200	454	386	93	-15	662	258	29	-61
20 Rest of Africa	764	1676	1562	105	-7	3783	2652	247	-30
21 Saudi Arabia	215	627	324	50	-48	1244	153	-29	-88
22 Arabian Emirates	71	166	109	54	-34	200	60	-16	-70
23 Rest of Middle East	573	1434	1110	94	-23	2853	716	25	-75
24 China	3843	8133	6356	65	-22	10580	2662	-31	-75
25 India	1539	3529	3230	110	-8	6116	2917	89	-52
26 Indonesia	414	1135	1043	152	-8	1914	743	79	-61
27 Korea (South)	144	165	98	-32	-40	239	47	-67	-80
28 Malaysia	93	308	246	164	-20	548	178	91	-68
29 Philippines	101	286	235	133	-18	615	221	120	-64
30 Singapore	32	90	62	96	-31	100	40	27	-60
31 Thailand	188	478	425	126	-11	769	341	81	-56
32 Rest of Asia	1094	2430	2185	100	-10	3651	2119	94	-42

Source: FAIR 2.1 world model

Note: Explanation of regions:

02 EU-15, Old EU Member states: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden and United Kingdom.

03 EU-10, New EU Member states: Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Slovakia, Slovenia.

04 Rest of Western Europe (rest of Western Europe): Iceland, Liechtenstein, Monaco, Norway, San Marino, Switzerland.

06 Rest of Eastern Europe (rest of Eastern Europe in Annex I): Belarus, Bulgaria, Croatia, Romania, Ukraine;

08 Rest of Annex I countries: Australia, Canada, New Zealand.

10 Rest of Eastern Europe: lbania, Armenia, Azerbaijan, Belarus, Bosnia & Herzegovina, Georgia, Kazakhstan, Kyrgyzstan, FYR Macedonia, Moldova, Serbia & Montenegro, Tajikistan, Turkmenistan, Uzbekistan.

15 Rest of Latin America: Bahamas, Barbados, Belize, Bolivia, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, Grenada, Guatemala, Guyana, Haiti, Honduras, Jamaica, Nicaragua, Panama, Paraguay, Peru, Saint Kitts & Nevis, Saint Lucia, Saint Vincent & Grenadines, Suriname, Trinidad & Tobago, Uruguay.

19 Rest of North Africa: Algeria, Libya, Morocco, Tunisia.

20 Rest of Africa: Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Dem. Republic Congo, Ivory Coast, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Rwanda, Sao Tome & Principe, Senegal, Seychelles, Sierra Leone, Sudan, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe.

23 Rest of Middle East: Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Syria, Yemen.

32 Rest of Asia: Afghanistan, Bangladesh, Bhutan, Brunei, Cambodia, Cook Islands, Fiji, Kiribati, Korea (North), Laos, Maldives, Marshall Islands, Federated States of Micronesia, Mongolia, Myanmar, Nauru, Nepal, Niue, Pakistan, Palau, Papua New Guinea, Samoa, Solomon Islands, Sri Lanka, Taiwan, Timor-Leste (East Timor), Tonga, Tuvalu, Vanuatu, Vietnam.

Table B.2 The emission allowances of countries or aggregated groups of countries under the Medium Technology scenario.

	1990	2020				2050			
	1990	Baseline	Target	Relative to 1990	Relative baseline	Baseline	Target	Relative to 1990	Relative baseline
	$MtCO_2$-eq	$MtCO_2$-eq	$MtCO_2$-eq	%	%	MtCO2-eq	$MtCO_2$-eq	%	%
Annex I countries	17282	23021	16218	-6	-30	24864	6127	-64.5	-75.4
Non-Annex I countries	13295	28532	24721	86	-13	45847	23357	75.7	-49.1
World	30577	51553	40939	34	-21	70711	29484	-3.6	-58.3
01 USA	6361	9452	6749	6	-29	11262	2054	-67.7	-81.8
02 EU-15	4101	5454	3515	-14	-36	5898	1603	-60.9	-72.8
03 EU-10	906	917	728	-20	-21	990	270	-70.2	-72.7
04 Rest of Western Europe	104	148	90	-14	-39	155	51	-51.6	-67.5
05 Russia	2834	2607	2286	-19	-12	2017	951	-66.4	-52.8
06 Rest of Eastern Europe in Annex I	623	935	639	3	-32	882	332	-46.8	-62.4
07 Japan	1214	1819	1105	-9	-39	1742	467	-61.6	-73.2
08 Rest of Annex I countries	1148	1705	1121	-2	-34	1940	411	-64.2	-78.8
09 Turkey	221	418	358	62	-14	713	393	77.7	-44.9
10 Rest of Eastern Europe	941	1712	1027	9	-40	2564	480	-48.9	-81.3
11 Argentina	260	432	398	53	-8	670	295	13.4	-56.0
12 Brazil	751	1435	1274	70	-11	2187	1064	41.8	-51.3
13 Mexico	484	906	818	69	-10	1464	616	27.3	-58.0
14 Venezuela	174	391	358	106	-8	706	272	56.1	-61.5
15 Rest of Latin Am.	568	1079	980	73	-9	1883	908	59.9	-51.8
16 Egypt	131	349	305	132	-13	615	397	203.2	-35.4
17 South Africa	396	669	625	58	-6	1112	287	-27.5	-74.2
18 Nigeria	126	330	310	147	-6	744	563	347.5	-24.4
19 Rest North Africa	200	454	416	108	-8	662	409	104.2	-38.2
20 Rest of Africa	764	1676	1587	108	-5	3783	2922	282.7	-22.7
21 Saudi Arabia	215	627	441	105	-30	1244	229	6.3	-81.6
22 Arabian Emirates	71	166	136	90	-18	200	81	13.9	-59.4
23 Rest of Middle East	573	1434	1269	121	-11	2853	1149	100.5	-59.7
24 China	3843	8133	6926	80	-15	10580	4358	13.4	-58.8
25 India	1539	3529	3203	108	-9	6116	3980	158.5	-34.9
26 Indonesia	414	1135	1035	150	-9	1914	1120	170.1	-41.5
27 Korea (South)	144	165	109	-25	-34	239	73	-49.5	-69.6
28 Malaysia	93	308	274	194	-11	548	271	190.4	-50.6
29 Philippines	101	286	251	149	-12	615	314	212.0	-48.9
30 Singapore	32	90	75	139	-16	100	55	74.6	-44.9
31 Thailand	188	478	430	129	-10	769	485	157.7	-36.9
32 Rest of Asia	1094	2430	2176	99	-10	3651	2680	144.9	-26.6

Source: FAIR 2.1 world model

Table B.3. The emission allowances of countries or aggregated groups of countries under the Slow Technology scenario.

	1990	2020				2050			
	1990	Baseline	Target	Relative to 1990	Relative to baseline	Baseline	Target	Relative to 1990	Relative to baseline
	$MtCO_2$-eq	$MtCO_2$-eq	MtCO2-eq	%	%	$MtCO_2$-eq	$MtCO_2$-eq	%	%
Annex I countries	17282	23021	18618	8	-19	24864	12224	-29	-51
Non-Annex I countries	13295	28532	26219	97	-8	45847	35971	171	-22
World	30577	51553	44837	47	-13	70711	48195	58	-32
01 USA	6361	9452	7873	24	-17	11262	4646	-27	-59
02 EU15	4101	5454	4092	0	-25	5898	3117	-24	-47
03 EU-10	906	917	813	-10	-11	990	679	-25	-31
04 Rest of Western Europe	104	148	99	-5	-33	155	79	-25	-49
05 Russia	2834	2607	2383	-16	-9	2017	1275	-55	-37
06 Rest of Eastern Europe in Annex I	623	935	730	17	-22	882	602	-3	-32
07 Japan	1214	1819	1324	9	-27	1742	969	-20	-44
08 Rest of Annex I countries	1148	1705	1320	15	-23	1940	873	-24	-55
09 Turkey	221	418	413	87	-1	713	660	198	-7
10 Rest of Eastern Europe	941	1712	1526	62	-11	2564	872	-7	-66
11 Argentina	260	432	407	56	-6	670	417	60	-38
12 Brazil	751	1435	1318	76	-8	2187	1377	83	-37
13 Mexico	484	906	840	74	-7	1464	1020	111	-30
14 Venezuela	174	391	369	112	-6	706	402	131	-43
15 Rest of Latin Am.	568	1079	1016	79	-6	1883	1266	123	-33
16 Egypt	131	349	315	141	-10	615	569	334	-8
17 South Africa	396	669	639	61	-4	1112	704	78	-37
18 Nigeria	126	330	316	151	-4	744	765	508	3
19 Rest North Africa	200	454	425	112	-6	662	620	210	-6
20 Rest of Africa	764	1676	1621	112	-3	3783	3555	366	-6
21 Saudi Arabia	215	627	589	173	-6	1244	708	229	-43
22 Arabian Emirates	71	166	163	129	-1	200	154	117	-23
23 Rest of Middle East	573	1434	1331	132	-7	2853	1832	220	-36
24 China	3843	8133	7191	87	-12	10580	8112	111	-23
25 India	1539	3529	3299	114	-7	6116	6098	296	0
26 Indonesia	414	1135	1064	157	-6	1914	1670	303	-13
27 Korea (South)	144	165	137	-5	-17	239	120	-17	-50
28 Malaysia	93	308	283	203	-8	548	450	382	-18
29 Philippines	101	286	257	155	-10	615	473	370	-23
30 Singapore	32	90	80	152	-12	100	89	183	-11
31 Thailand	188	478	445	137	-7	769	689	266	-10
32 Rest of Asia	1094	2430	2245	105	-8	3651	3405	211	-7

Source: FAIR 2.1 world model