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FAIR 2.0 – A decision-support tool to assess the environmental and economic consequences of future climate regimes

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Abstract

This report describes the policy decision-support-tool FAIR 2.0 (Framework to Assess International Regimes for the differentiation of commitments). The main objective of this model is to support policy makers in assessing the environmental and economic implications of international climate regimes for differentiation of future commitment beyond 2012 compatible with the Climate Change Convention objective of stabilising the atmospheric concentrations of greenhouse gases (Article 2). The FAIR 2.0 model represents an integration of three sub-models: 1. A *climate model* for the evaluation of the climate impacts of global emission profiles and the calculation of the regional contributions to climate change. 2. An *emissions-allocation model* to explore and evaluate the emission allowances for different climate regimes for the differentiation of future commitments (such as the Brazilian Proposal, Multi-Stage approach, Contraction & Convergence, Triptych approach and other regimes). 3. A *mitigation costs and emission trading model* to distribute the emission reduction objective over the different regions, gases and sources following a least-cost approach, to calculate the international permit price and determine the buyers and sellers on the international trading market and to calculate the regional mitigation costs and emission reductions after trading.

Summary

This report describes the policy decision-support tool, FAIR 2.0 (Framework to Assess International Regimes for the differentiation of commitments). The main objective of this model is to support policy makers in assessing the environmental and economic implications of international climate regimes for differentiation of future commitment beyond 2012 compatible with the Climate Change Convention objective of stabilising the atmospheric concentrations of greenhouse gases (Article 2). Other objectives are to evaluate the Kyoto Protocol after the Bonn and Marrakesh agreements in terms of environmental effectiveness and economic costs, and to support the dialogue between scientists and policy makers. The FAIR 2.0 model represents an integration of three sub-models: 1. A *climate model* for evaluating the climate impacts of global emission profiles and calculating the regional contributions to climate change. 2. An *emissions allocation model* to explore and evaluate the emission allowances for different climate regimes for the differentiation of future commitments. 3. A *mitigation-cost and emission-trading model* to distribute the emission reduction objective over the different regions, gases and sectors following a least-cost approach, to calculate the international permit price and determine the buyers and sellers on the international trading market, and to calculate the regional mitigation costs and emission reductions after trading.

The model includes five groups of regimes for differentiating future commitments, i.e.: the Multi-Stage approach, Brazilian Proposal, Contraction & Convergence, Emissions Intensity system approach and the Triptych approach. The different climate regimes can be evaluated for their climate impacts (e.g. temperature increase and sea-level rise), regional emission reduction objectives and regional mitigation costs or gains (resulting from emission trading).

In addition to the three sub-models, the model includes a database system, encompassing different data sets for historical emissions, baseline scenarios, emission profiles, climate models and marginal abatement cost functions. This gives the user complete flexibility and the possibility to evaluate the robustness of the different climate regimes in relation to scientific uncertainties.

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Analyses with the FAIR model as well as the model itself has been presented at various international conferences and workshops. We would like to thank the many participants of these meetings for their participation in fruitful scientific discussions and their comments.

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Contents

Samenvatting

Dit rapport beschrijft het beleidsondersteunende model FAIR 2.0 (Framework to Assess International Regimes for differentiation of commitments). FAIR is een interactief computer model voor het (kwantitatief) evalueren van de milieueffectiviteit en economische kosten van verschillende benaderingen voor internationale lastenverdeling voor het klimaatbeleid, welke in overeenstemming zijn met Artikel 2 van het internationale Klimaatverdrag UNFCCC: de stabilisatie van de concentraties van broeikasgassen op een ‘veilig’ niveau. Andere doelstellingen zijn: het evalueren van het Kyoto Protocol na het Bonn-Marrakesh akkoord, en het ondersteunen van de dialoog tussen klimaatwetenschappers, NGOs en beleidsmakers.
Het FAIR 2.0 model bevat drie deelmodellen: 1. Een *klimaat model* voor de evaluatie van de klimaateffecten van een mondiaal emissieplafond en de berekening van de regionale bijdrage aan klimaatsverandering. 2. Een *emissieallocatie model* voor het verkennen en evalueren van de toegestane emissieruimte voor de verschillende benaderingen voor internationale lastenverdeling voor het klimaatbeleid. 3. Een *mitigatie-kosten en emissie-handel model* voor de kosteneffectieve verdeling van de emissie reductie doelstelling over de verschillende regio’s, gassen en bronnen. Het model berekent de prijs op de internationale emissiemarkt, de kopers en verkopers op deze markt, de totale mitigatie-kosten en de regionale emissie reducties na handel.
Het model omvat vijf groepen van benaderingen voor internationale lastenverdeling: ‘Multi-Stage’ (MS) (toenemende participatie), Braziliaans voorstel, Per Capita Convergentie (PCC) of ‘Contraction & Convergence’, emissie-intensiteit systemen en de Triptiek benadering. De verschillende regimes kunnen worden geëvalueerd met betrekking tot de klimaateffecten (bijvoorbeeld de temperatuur- en zeespiegelstijging), de regionale inspanningsniveaus en de regionale mitigatie-kosten of baten (ten gevolge van emissiehandel).
Naast de drie deelmodellen bevat het FAIR model ook een databasesysteem met verschillende datasets voor historische emissies, baseline scenario’s, emissieplafonds en marginale kosten curven. Dit geeft de gebruiker de mogelijkheid om de robuustheid van de resultaten te evalueren met betrekking tot de verschillende wetenschappelijke onzekerheden.

1 Introduction

Climate change is a global problem. It does not matter where greenhouse gases are emitted. The change in climate that results from the increasing greenhouse gas concentrations is felt across the world. The driving forces for greenhouse gas emissions are found in the main contributors to development: population, economic growth, land-use and the choice of technology. Greenhouse gas emission projections for the baseline scenarios for the next hundred years range from emissions returning to approximately current levels to a seven-fold increase in the absence of climate mitigation actions. Furthermore, there will be a continuing rise in the concentrations of greenhouse gases throughout the 21st century (Nakicenovic et al., 2000). However, the long-term objective of the United Nations Framework Convention on Climate Change (UNFCCC) is to achieve 'stabilisation' of atmospheric greenhouse gas levels at non-dangerous levels (Article 2) (UNFCCC, 1992). This would mean roughly a 50% reduction of current global greenhouse gas emissions (IPCC, 1996b).

With this in mind, one of the most contentious issues in international climate policy development is the issue of (international) burden sharing or differentiation of (future) commitments: Who should contribute when and how much to reducing the global greenhouse gas emissions? It is an issue related to both technical capabilities and economic costs, as well as considerations on responsibility and equity. This report describes the policy decision-support tool, FAIR 2.0 (Framework to Assess International Regimes for the differentiation of commitments), which tries to cover most of these issues quantitatively.

The major objective of the FAIR 2.0 model is to assist policy makers in exploring and evaluating different international climate regimes for differentiation of future commitments under the Climate Change Convention (post-Kyoto) in the context of stabilising GHG concentrations (Article 2). Many approaches for differentiation of commitments in international climate policy making have been proposed over the years, both in academic and policy circles (Depledge, 2000; Ringius et al., 1998; Torvanger and Godal, 1999). The FAIR model does not intend to promote any particular approach to international burden sharing. Instead, the FAIR 2.0 model aims to support policy makers by quantitatively evaluating the environmental, economic and distributional implications of a range of the most widely known approaches and linking these to targets for global climate protection.

Other objectives of the model are to evaluate the Kyoto Protocol after the Bonn Agreement and Marrakesh Accords in terms of environmental effectiveness and economic costs, and to support the dialogue between scientists, NGOs and policy makers. The FAIR model is then an interactive policy tool with a graphical interface, allowing for interactive changing and viewing model input and output.

Historical background
The FAIR 1.0 model was developed at the National Institute for Public Health and the Environment (RIVM), starting in 1998 with the evaluation of the scientific and methodological aspects of the Brazilian Proposal for the Dutch Ministry of Environment (Berk and den Elzen, 1998; Berk and den Elzen, 2001; den Elzen et al., 1999). Since then, the FAIR 1.0 model has been used in several policy-supporting exercises, such as the analysis of post-Kyoto climate regimes for differentiation of future commitments for the National Environmental Outlook (Berk et al., 2002a). The FAIR 1.0 model was put on Internet (www.rivm.nl/fair) at the beginning of 2001 (den Elzen et al., 2001). The

interactive attributes of FAIR 1.0 have been put to use in several workshops in the context of the international science policy dialogue between international scientists, policy makers and NGOs as part of the COOL project (Berk et al., 2002b). In 2001, the model was extended with a cost model and updated to FAIR 1.1. This model has been used for the evaluation of the environmental effectiveness and economic costs consequences of the Kyoto Protocol under the Bonn and Marrakech agreements for the Dutch Ministry of Environment (described in den Elzen and de Moor (2001a; 2001b). It has also been employed in the evaluation of the Bush Climate Change Initiative (de Moor et al., 2002a). In 2002, the model was used in the framework of the UNFCCC project entitled 'Assessment of Contributions to Climate Change' (UNFCCC-ACCC) (UNFCCC, 2002a), as described in den Elzen et al. (2002). This year (2003) the model has been improved with various new regime approaches, while emission allocation and cost calculations are now at the level of CO_2-equivalent emissions instead of (fossil) CO_2 only. This has led to FAIR 2.0, a version that has been used for the evaluation of post-Kyoto climate regimes for future commitments as part of the EU project, 'Greenhouse Gas Reduction Pathways in the UNFCCC Post-Kyoto process up to 2025'[1] (see, for example, den Elzen et al. (2003b)). Other scientific applications of the FAIR 2.0 model are, in combination with the IMAGE-TIMER model, the analysis of multi-gas mitigation scenarios in the Emission Modelling Forum (EMF 21). Table 1.1 summarises the main policy applications of the FAIR 2.0 model, indicating the event at which they were presented. Table 1.2 presents the scientific and educational applications.

Table 1.1. Policy applications of the FAIR model from 1998 to 2003

Year	Activity	Presented at
1998 – 1999	Evaluation of the Brazilian Proposal and other regimes	COP4, TKP*
1999 – 2001	Interactive use in the international dialogue between scientists, NGOs and policy makers (COOL project)	COOL workshops, COP6, TKP
2001	Analysis of post-Kyoto climate regimes for differentiation of commitments for the National Environmental Outlook	COP6, TKP
2001 – 2002	Evaluation of the Kyoto Protocol after the Bonn and Marrakech agreements	COP7, TKP
2002	Evaluation of the Bush Climate Change Initiative	TKP
2002	UNFCCC 'Assessment of Contributions to Climate Change' (UNFCCC-ACCC)	COP8, TKP
2002 – 2003	Evaluation of climate regimes for the differentiation of future commitments for the Dutch Ministry of Environment, EU commission, i.e. DG Environment	TKP EU-DG ENV
2003	FAIR workshop on post-Kyoto climate regimes	NOA–Greece, WTV**

* TKP - Task Group on Kyoto Protocol (Interdepartmental working group of various national ministries)
** WTV - Working Group for further action (interdepartmental working group representing various national ministries)

Table 1.2. Scientific and educational applications of the FAIR model from 1998 to 2003

Year	Activity
1999 – 2003	Presentation at many universities, institutes and other organisations (IEA, OECD, WRI, UNFCCC, NOA, IEPE, University of Kassel, EU commission, etc.)
2001 – 2003	FAIR 1.0 Internet (FAIR user group: ~500 users)
2002 – 2003	FAIR 1.0 course at Open University UK (FAIR DVD)
2002 – 2003	Energy Modelling Forum (EMF) - mitigation-scenarios for all GHGs in combination with IMAGE/TIMER model
1999 – 2003	FAIR analyses in 13 scientific articles, 2 book contributions, 15 RIVM reports and 2 EU reports (see www.rivm.nl/fair)

[1] EU Research Contract B4-3040/2001/325703/MAR/E.1 for DG Environment.

Overview of the FAIR 2.0 model

The FAIR 2.0 model[2] now consists of three models:

1. A *climate model*: to calculate the climate impacts of global emission profiles or emission scenarios and the regional contributions to climate change indicators, e.g. global temperature increase.
2. An *emission allocation model*: to explore and evaluate the emission allowances for differentiation of future commitments for ten climate regimes of the world regions (e.g. the Brazilian Proposal, and Multi-Stage, Contraction & Convergence, Emission Intensity Target, Triptych).
3. A *mitigation costs and emission trading model*: to evaluate the economic implications of a future commitment regime under different emission trading markets and to spread the emission reduction objective over the different regions, gases and sectors following a least-cost approach.

Organisation of the report

Chapter 2 overviews the model structure and briefly describes the new features in comparison to the FAIR1.0 version. Chapter 3 describes the data sets used and Chapters 4 to 6, the three (sub-) models.

[2] A demonstration version of FAIR 2.0 can be downloaded from Internet after 1 November (http://www.rivm.nl/fair). A full version of the model will be made available on a limited basis to non-profit research and educational institutions, or national ministries, and only for non-commercial applications. This will be decided on a case by case basis.

2 The FAIR 2.0 model

2.1 Overview of the model

The FAIR 2.0 model consists of three sub-models as outlined below – a simple climate model, an emission allocation model and a mitigation costs and emissions trade model (Figure 2.1):

1. The *climate model* calculates the greenhouse gas concentrations, radiative forcing of GHGs and other reactive gases (aerosols), global temperature increase, rate of temperature increase, as well as the sea-level rise for the global emission scenarios and GHG emission profiles associated with different levels of GHG concentration stabilisation targets. A special climate attribution submodel calculates the regional contribution to global temperature increase and other climate indicators on the basis of the effect of their historical emissions.
2. The *emission allocation model* calculates regional emission allowances for ten future commitment approaches, divided into five groups:
    a. The Multi-Stage approach: a top-down approach[3] with a gradual increase in the number of countries involved and their level of commitment according to participation and differentiation rules, such as per capita income or per capita emissions (Berk and den Elzen, 2001). A more simplified Multi-stage approach is included here too, with fewer stages and policy variables, and with threshold levels based on the so-called Capability-Responsibility index (den Elzen et al., 2003a).
    b. The Brazilian Proposal approach: a top-down approach allocating emission reductions on the basis of contribution to global temperature increase combined with an income threshold for participation for the non-Annex I regions (den Elzen et al., 1999).
    c. Convergence approaches: top-down approaches in which emission allowances are calculated on the basis of convergence rules. Four types of convergence regimes are included:
        (i) 'Contraction & Convergence', or Per Capita Convergence, i.e. emission allowance convergence towards equal per capita emissions (Meyer, 2000);
        (ii) CSE convergence: the Contraction & Convergence approach with basic sustainable emission rights, as introduced by the Centre of Science and Environment (CSE) (CSE, 1998);
        (iii) Preference Score approach: a combination of the grandfathering entitlement method and a per capita convergence approach (Bartsch and Müller, 2000).
        (iv) Multi-criteria convergence: distribution of commitments based on different weighting of criteria (population, GDP and emissions).
    d. Emission intensity system approaches: the emission intensity of the economy is the emissions per unit of economic activity expressed in Gross Domestic Product (GDP). Three types of emission intensity systems are included:
        (i) Emission Intensity Convergence approach: a top-down approach with convergence of emission intensities;
        (ii) Emission Intensity Targets approach: a bottom-up approach[4], in which all regions adopt GHG intensity targets right after 2012 when achieving an income threshold.

[3] A top-down approach first defines the global GHG emission profile (budget) and then allocates the emission allowances or reductions.
[4] A bottom-up approach calculates the emission allowances without a pre-defined emission profile.

(iii) Jacoby Rule approach: a bottom-up approach, in which both participation and emission reductions depend on the per capita income (Jacoby et al., 1999). This approach can also be applied top-down by scaling total emissions in the direction of the emission profile.

e. Triptych approach: a sector and technology-oriented bottom-up approach in which overall emission allowances are determined by applying various differentiation rules to different sectors (e.g. convergence of per capita emissions in the domestic sector, efficiency and de-carbonisation targets in the industrial and the power generation sector) (Blok et al., 1997; Phylipsen et al., 1998).

3. The *mitigation costs and emissions trade model* calculates the tradable emission permits, the international permit price and the total abatement costs, with or without emission trading, according to the regional emission allowances of a certain climate regime. The model makes use of Marginal Abatement Cost curves (MACs)[5] used to derive permit supply and demand curves under different regulation schemes in any emissions trading market using the same methodology as Ellerman and Decaux (1998).

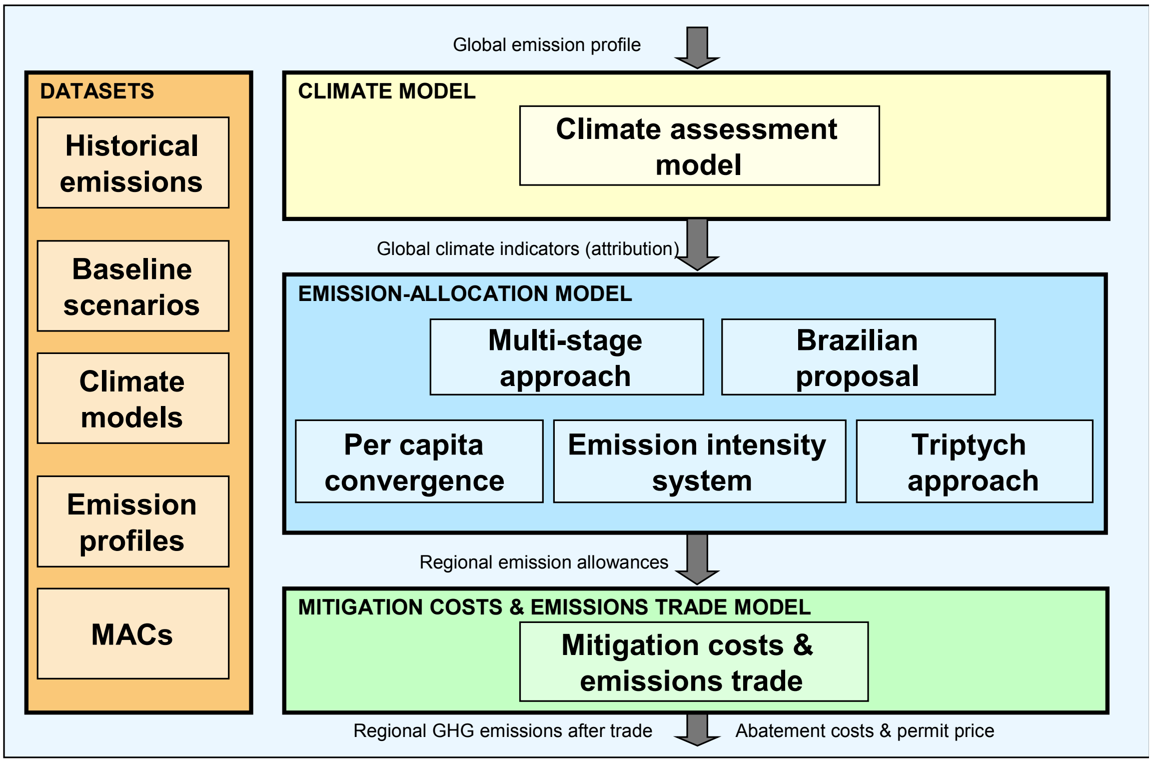

Figure 2.1. Schematic diagram of FAIR 2.0 showing its framework and linkages.

2.2 New elements of FAIR 2.0

Since 2001, the FAIR 1.0 model (den Elzen et al., 2001) has undergone numerous major and minor modifications, with several new elements being introduced, leading to the present FAIR 2.0 model. These new elements are briefly summarised here:

1. An increase in the number of world regions – from 13 to 17 – in line with the IMAGE 2.2 world regions. These are Canada, USA, Central America, South America, Northern Africa, Western Africa, Eastern Africa, Southern Africa, OECD Europe, Eastern Europe, Former USSR (FSU), Middle East, South Asia (including India), East Asia (including China), South East Asia, Oceania and Japan (see Figure 2.2).

[5] A marginal abatement curve (MAC), differing per country, reflects the additional costs of reducing the last unit of carbon.

2. All emission allocation and cost calculations now at the level of CO_2-equivalent emissions instead of (fossil) CO_2-only.[6]
3. Historical emission datasets now based on the latest EDGAR-HYDE 1.4 historical emissions database (all GHGs and other reactive gases), with the energy and industry-related CO_2 emissions, and the land-use-related CO_2 emissions, based on the latest CDIAC-ORNL database.
4. The set of baseline emission scenarios updated with the new IMAGE 2.2 IPCC SRES emission scenarios (IMAGE-team, 2001), along with the original IPCC SRES scenarios (Nakicenovic et al., 2000). The recently developed Common POLES-IMAGE (CPI) emission scenario is also included.
5. Inclusion of new IMAGE 2.2 emission profiles, stabilising the atmospheric CO_2-equivalent concentrations[7] at different levels (550, 650 and 750 ppmv) (Eickhout et al., 2003).
6. Replacement of the climate model by the stand-alone IMAGE 2.2.version of the Atmosphere-Ocean System (AOS). For alternative climate calculations, the climate model also includes alternative simple carbon-cycle and climate models of the UNFCCC, along with the Impulse Response Functions (IRFs) based on simulation experiments with nine general circulation and other climate models.
7. Improvement of the climate 'attribution' module for calculating the regional contributions to global climate indicators using the recent UNFCCC methodology.[8]
8. An updated Triptych approach methodology, including all GHG emissions, as well as improvements to the convergence regime. New climate regimes like Global Compromise, Jacoby rule and different emission intensity systems are also included.
9. Extension of the Multi-Stage regime with a new participation threshold based on both per capita income and per capita emissions, called the Capability-Responsibility (CR) index (den Elzen et al., 2003a). Other new elements include: (i) accounting for a policy delay between passing thresholds and taking action; (ii) using a reference period for calculating threshold levels and (iii) making income-dependent GHG intensity improvements in stage 2.
10. The new mitigation costs and emissions trade model used to analyse the economic implications of a future commitment regime under different emission trading markets.
11. The possibility of evaluating the Kyoto Protocol and its flexibility; the implementation of US intensity targets.

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[6] Similar to the Kyoto Protocol (KP), the GHG emissions targets are calculated as CO_2-equivalent emissions, i.e. the sum of the Global Warming Potential (GWP)-weighted emissions of six specified GHG emissions or groups of gases covered in the Kyoto Protocol. These are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6).

[7] CO_2-equivalent concentration is a measure of the contribution of the various GHGs to the radiative forcing in any given year in terms of CO_2.

[8] http://unfccc.int/program/mis/brazil/

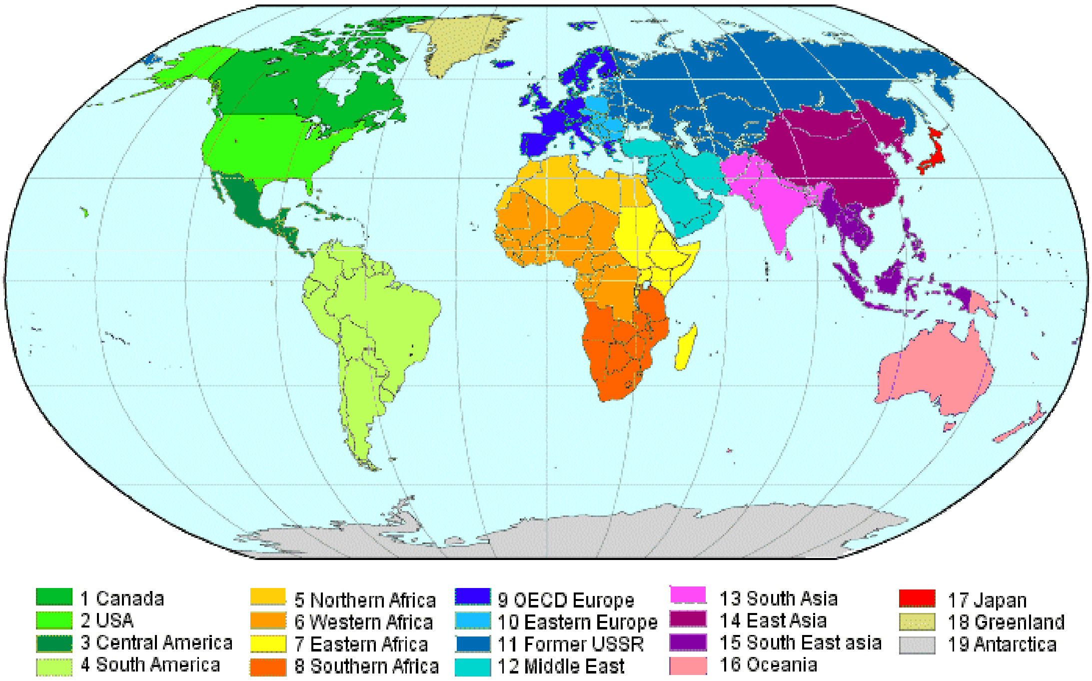

Figure 2.2. The seventeen IMAGE 2.2 world regions (IMAGE-team, 2001) .

3 Datasets of FAIR 2.0

3.1 Historical emissions data

The historical emission datasets cover the greenhouse gases, CO_2, CH_4, N_2O and the halocarbons (only those covered by the Kyoto Protocol) for the period from 1760 to 1995 and are mainly used by the climate model. The emissions are based on the CDIAC-ORNL database (Andres et al., 1998; Marland et al., 1999) and EDGAR 1.4 (Emission Database for Global Atmospheric Research) database (Olivier and Berdowski, 2001; Van Aardenne et al., 2001). The CDIAC-ORNL database includes the CO_2 emissions from fossil fuel combustion and cement production for 1751-1995 on country level, and the regional CO_2 emissions from land-use changes, based on Houghton (1999). The EDGAR 1.4 database includes historical emissions of the greenhouse gases, CO_2, CH_4, N_2O, the halocarbons and F-gasses from fossil fuel combustion[9], industrial and agricultural sources, and emissions from biomass burning and deforestation for 1890-1995. The historical emissions of all gases included occur at the level of IMAGE 2.2 regional aggregation of 17 world regions (see Figure 2.2).[10]

Table 3.1. The different historical emission datasets included

Historical emission datasets
• CDIAC (energy, industrial & CO_2 land-use emissions)
• EDGAR/HYDE (GHG emissions: energy, industry & land use and agriculture)

3.2 Baseline scenarios

The baseline scenarios are used for future (1995-2100) projections of population, Gross Domestic Product (GDP) (in US$ or PPP$)[11] and baseline emissions of GHGs (without climate policy). Different types of baseline scenarios are included (see Table 3.2). The IMAGE 2.2 IPCC SRES emission scenarios are extensively described in IMAGE-team (2001) and the original IPCC SRES scenarios in Nakicenovic et al. (2000).[12] The common POLES-IMAGE (CPI) emission scenario (see den Elzen et al. (2003a)) is largely based on the existing POLES reference scenario up to 2030 (Criqui and Kouvaritakis, (2000) and extended to 2100 by using the IMAGE 2.2 model (IMAGE-team, 2001).

Table 3.2. The different baseline scenarios included

Baseline scenarios
• Six IMAGE 2.2 IPCC SRES emission scenarios
• Six original IPCC SRES emission scenarios
• Common IMAGE-POLES (CPI) emission scenario

[9] The bunker CO_2 emissions can be treated as a separate region, but may also be included in the regional emissions.

[10] To this end, only the regional CO_2 emissions from the Houghton land-use changes had to disaggregate at the level of our IMAGE 2.2 regions using historical population data.

[11] The Purchase Power Parity (PPP) is an alternative indicator for GDP per capita, based on relative purchasing power of individuals 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 United States.

[12] We used the detailed regional information of our own IMAGE 2.2 implementation of the IPCC SRES emissions scenarios (IMAGE-team, 2001) for disaggregating the regional emissions of the IPCC SRES scenarios at the level of the IMAGE 2.2 regions.

3.3 Emission profiles

The emission profiles describe emission pathways up to 2100, and even to 2300, leading to a stabilisation of the CO_2-equivalent concentrations[13] at different levels. The FAIR 2.0 model includes the IMAGE 2.2- and IPCC-SAR emission profiles (Table 3.3). The IMAGE 2.2 GHG emission profiles result in a stabilisation of the CO_2-equivalent concentrations at 550, 650 and 750 ppmv in 2100, 2150 and 2150, respectively (S550e, S650e and S750e profiles), (Eickhout et al., 2003). The corresponding CO_2 emission profiles result more-or-less in a stabilisation of the respective CO_2 concentrations of 450, 550 and 650 ppmv for S450c, S550c and S650c profiles. The range in the temperature increase associated with these two profiles will depend on the uncertainty attached to the 'climate sensitivity' parameter. The S550e profile may result in a maximum global mean temperature increase of less than 2°C, with a low to medium level of climate sensitivity, defined as the equilibrium global mean surface-temperature increase resulting from a doubling of CO_2-equivalent concentrations. The IPCC estimates the range of the climate sensitivity between 1.5 and 4.5°C, with a median value of 2.5°C (sensitivities near the median are much more likely than sensitivities near the outer ends). The S650e profile only remains below this level if the climate sensitivity level is low. Consequently, this profile is unlikely to meet the EU target. For the S750e profile this is even more unlikely. In the case of a serious climate sensitivity, the EU target will not be met under all three profiles.

The IPCC-SAR CO_2-only emission profiles are the CO_2 emission profiles based on inverse calculations (e.g. Enting et al. (1994)) with the Bern carbon cycle model of Joos et al. (1996; 1999) using the delayed response concentration stabilisation profiles of Wigley et al. as input (Wigley et al., 1996). The corresponding CO_2-only emission profiles stabilise the CO_2 concentrations at 450 and 550 ppmv (WRE S450c and WRE S550c profile).

Users can also construct their own CO_2-only emission profile, which can be combined with the non-CO_2 emissions from the IMAGE 2.2 emission profiles to create a multi-gas profile. This profile can then be evaluated with respect to its climate impacts and can be used in the emission allocation model.

Up to 2012 all emission profiles incorporate the implementation of the Annex I Kyoto Protocol targets, an optimal level of banking excess emissions by the Former Soviet Union (FSU) and Eastern Europe and adoption of the proposed greenhouse gas intensity target for the USA (-18% between 2002-2012) (van Vuuren et al., 2002; White-House, 2002a).

Table 3.3. The different emission profiles included

Emission profiles
• Three IMAGE 2.2 GHG emission profiles, resulting in stabilisation of the CO_2-equivalent concentration at 550, 650 and 750 ppmv (S550e, S650e and S750e profiles).
• Three IMAGE 2.2 CO_2-only emission profiles, resulting in stabilisation of the CO_2 concentration at 450, 550 and 650 ppmv (S450c, S550c and S650c profiles).
• Two IPCC-SAR CO_2-only emission profiles, resulting in stabilisation of the CO_2 concentration at 450 and 550 ppmv (WRE S450c and WRE S550c profiles).
• User-owned defined CO_2-only emission profile.

[13] CO_2-equivalent concentration is a measure of the contribution of the various GHGs to the radiative forcing in any given year in terms of CO_2.

3.4 Climate models

Table 3.4 lists the climate models included in the FAIR model. The IMAGE-AOS climate model is used for the default global climate calculations. For alternative calculations, either the UNFCCC-ACCC climate model, or eight alternative climate models based on Impulse Response Functions (IRFs) (as explained in Box 1 in Chapter 4) can be used. The IRFs are calculated on the basis of simulation experiments with various Atmosphere-Ocean General Circulation Models (AOGCMs).

Table 3.4. The different climate models included

Climate models
• IMAGE-AOS climate model
• UNFCCC-ACCC climate model
• Eight alternative climate models based on IRFs (Table 4.4).

3.5 Marginal Abatement Cost (MAC) curves

This section starts with a brief introduction to Marginal Abatement cost (MAC) curves explaining what MAC curves are and what they represent. How are MAC curves constructed from the macro-economic model WorldScan and the energy system model TIMER and how are they calculated in more bottom-up studies?

3.5.1 What are Marginal Abatement Cost (MAC) curves?

A MAC curve reflects the additional costs of reducing the last unit of carbon and is upward-sloping: i.e. marginal costs rise with the increase of the abatement effort. Figure 3.1 shows a stylised Marginal Abatement Cost curve. The point (q,p) on the curve represents the marginal cost, p, of abating an additional unit of carbon emissions at quantity q. The surface under the curve (hatched area) represents the total abatement costs of carbon emission reduction q. In this way the MAC curves, representing the costs and potential of emission reductions for the different regions, gases and sources, are used by the emission trading and abatement costs models and (see Chapter 6)[14].

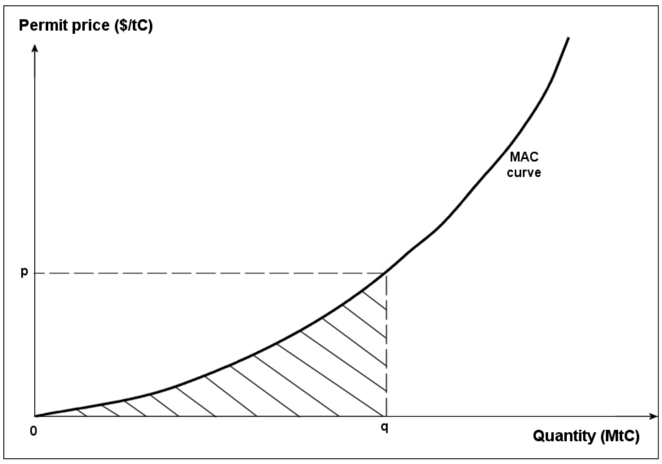

Figure 3.1. Marginal Abatement Cost Curve. The hatched area indicates the total cost of abatement under emission reduction objective q.

[14] One great advantage of using MAC curves is that they clearly show the effects of permit trading. However, there are also some limitations: carbon leakage cannot be taken into account, and while total abatement costs are reflected by MACs, welfare losses are not (see section 6.2).

3.5.2 *How are MAC curves constructed?*

Macro-economic and energy system models are used as examples for constructing MAC curves for CO_2 energy-related emissions, for which a carbon tax on fossil fuels is imposed to induce emission abatements. Such a tax is differentiated according to the CO_2 emissions (the carbon content) from the fuels. In response, emissions will decrease as a result of such measures as fuel switching (e.g. from coal to gas), decreases in energy consumption and the introduction of zero-carbon energy options (renewables and nuclear). The carbon tax can be seen as an indicator of the marginal abatement costs. MAC curves can be created by plotting different tax levels against the corresponding emission reductions i.e.:

1. Working with a reference projection (baseline) in which the carbon tax is zero.
2. Calculating by successive simulations, the emission reduction levels (*q*) associated with the carbon tax (*p*) through successive simulations that change from level to level.
3. Developing the MAC curve as illustrated in Figure 3.1 on the basis of the points (*q,p*).

Opposite to the above described top-down method, MAC curves can also be constructed through a bottom-up approach. In a bottom-up approach, the MAC curves are constructed according to detailed abatement options per gas and source. The different options are sorted according to their relative costs and plotted against their reduction potential. The fitted line then forms the MAC curve. To use the MAC curves for the different baseline scenarios of the various models, we have to express the MACs as percentile reductions with respect to the baseline emissions. Absolute MAC curves can be created by projecting the relative MAC curves on to the baseline emissions used in the FAIR model.

3.5.3 *The different MAC curves in the FAIR model*

Table 3.5 shows the different sets of MAC curves included in the FAIR model, with the models and background of the MAC curves explained below. The final MAC curves, as implemented in the FAIR model, are described in more detail in Appendix A.

Table 3.5. The different sets of MAC curves in the FAIR model

- CO_2 MAC curves (energy- and industry-related CO_2 emissions) from the energy system models, TIMER and POLES, and the macro-economic model, WorldScan.
- CO_2 sequestration MAC curves from the IMAGE 2.2 model.
- Non-CO_2 MAC curves from the GECS project and EMF 21.

CO_2 MAC curves of WorldScan

WorldScan is a multi-sector, multi-region applied general equilibrium model[15] (CPB, 1999). The model is developed for exploring long-term economic scenarios, with a focus on long-term growth and trade in the world economy based on neo-classical theories of growth and trade. The model can produce carbon shadow prices for any constraint on carbon emissions, but also the other way around, producing emission reductions compared to the baseline levels for any shadow price. The MAC curves of WorldScan do not change significantly with time. The reason for this is that the model does not include carbon-tax induced technological developments (learning) or limitations in time delays of implementing the options. Effects that can be of influence over time include structural economic changes, however, their impact seems.

[15] The WorldScan model MAC curves for April 2001 (CPB, 1999).

CO_2 MAC curves of TIMER

The TIMER (Targets Image Energy Regional model) model aims to analyse the long-term dynamics of the energy system, particularly with regard to energy conservation and the transition to non-fossil fuels. It also calculates energy-related greenhouse gas emissions (de Vries et al., 2002; van Vuuren and de Vries, 2001). An important aspect of the model is the modelling of technological development in terms of log-linear learning curves according to which the efficiency of processes improves with accumulated output (‘learning-by-doing’). These processes are price-induced energy efficiency improvements, fossil fuel production, non-fossil-based electricity and biofuels (van Vuuren and de Vries, 2001). Use of learning curves implies a path-dependent potential for technological change. Another important aspect is the limitations set on capital turnover. The fact that capital depreciation is limited within the model by its average lifetime introduces inertia between the signal (carbon price or tax) and the responses mentioned, which is crucial for the MAC curves. Both the learning effect and the delays make the actual MAC curve for each region dependent on earlier abatement action.

CO_2 MAC curves of POLES

POLES (Prospective Outlook on Long term Energy Systems) is a worldwide sectoral energy model that simulates energy demand and supply on a year-to-year basis up to 2030 (Criqui et al., 1999). The model includes 38 countries or regions and 15 main energy demand equations for each country, 24 power generation technologies, of which 12 new and renewable technologies are explicitly incorporated. The POLES model also projects the energy sector’s CO_2 emissions up to 2030, as well as the marginal abatement cost curves for these emissions in each of the 38 countries or regions. Inertia and technological learning similar to TIMER are modelled in POLES.

CO_2-sequestration MAC curves of IMAGE 2.2

The CO_2-sequestration MAC curves describe the potential and costs of carbon sequestration from afforestation activities. Population growth, technological development of the agricultural sector and the production of food and feed determines the amount of land in each region required to feed the world population, to fulfil the demand for timber and to grow modern biofuels. Land that is no longer required can be used for other purposes like sink sequestration. The IMAGE 2.2 model (IMAGE-team, 2001) is used to determine the area of land that will become available in a certain baseline period and how much carbon can be potentially sequestered in that area. The Surplus Potential Productivity (SPP) of the plantation is calculated to take into account the amount of carbon that would be sequestered by the re-growing vegetation of abandonment agricultural land. The SPP represents the net C sequestration by the plantation minus that of the original vegetation. The carbon plantations are assumed to be implemented in areas that have no other use during a 50-year period given the baseline. The SPP information for each 0.5 x 0.5 degree grid cell is aggregated to the level of the 17 regions, while the annual C sequestration is calculated as a mean during a 50-year period. The carbon supply curves form the basis of the sink MAC curves by taking into account the cost of land, and the forest establishment and the operation and maintenance costs. The differences in prices of land between regions result from differences in land and soil quality. The settlement costs are taken from the IPCC (1996a) and the operation and maintenance costs estimated as a standard value of $25 per hectare for OECD Europe and a variable value for the other regions on the basis of per capita incomes. The potential sink area is reduced by a factor representing political, social and economic obstacles. These barriers cause a reduction in the area through an implementation degree of 10% in 2010 and 30% in 2030 and onwards, so that the actual potential is only this percentage of the full potential.

Non-CO_2 MAC curves from the GECS project

The GECS project (Greenhouse gas Emission Control Strategies) (Criqui, 2002) is a European multi-partner project in the DG Research 5th Framework Program. The project was implemented to enhance the European capabilities for the economic analyses of long-term (2030) multi-gas abatement strategies in the perspective of future climate negotiations. The non-CO_2 MACs developed in this project have been constructed mostly on the basis of detailed abatement options per gas and per source (bottom-up). Eleven different sources for three different sectors for five non-CO_2 GHGs are distinguished per region (see Table 3.6).

Table 3.6. Sectoral non-CO_2 MAC curves from the GECS project

Gas	Sector	Sources
CH_4	Energy	Oil production (losses/leakage)
	Energy	Gas production (losses/leakage)
	Energy	Coal production (losses/leakage)
	Land-use	Waste (landfills and sewage)
	Land-use	Wetland rice, animals and animal waste
N_2O	Energy	Transport
	Industry	Adipic and nitric acid production
	Land-use	Fertiliser and animal waste
HFCs	Total	Total
PFCs	Total	Total
SF_6	Total	Total

Non-CO_2 MAC curves from EMF 21

The non-CO_2 MAC curves from EMF 21 are also constructed on the basis of detailed abatement options per gas and per source. Eight different sources for the five non-CO_2 GHGs are distinguished per region (see Table 3.7). The HFCs, PFCs and SF_6 are considered as one group (F gases) for which one MAC curve is available. The list of abatement options is compiled from analyses for the USA (USEPA, 1999; USEPA, 2001a; USEPA, 2001b), the EU (EC, 2000; EC, 2001) and the ICF (2002). Expert knowledge of the region is used to omit options from individual regions on a case-by-case basis. Each abatement option is characterised in terms of its costs and benefits. The costs include capital and maintenance costs, while the benefits include the value of methane, either as natural gas or electricity, the non-GHG benefits of the abatement option and the value of abating the GHG.

Table 3.7. Sectoral non-CO_2 MAC curves from EMF 21

Gas	Sector	Sources
CH_4	Energy	Oil production (losses/leakage)
	Energy	Gas production (losses/leakage)
	Energy	Coal production (losses/leakage)
	Land-use	Manure management
	Land-use	Landfills
N_2O	Industry	Adipic acid production
	Industry	Nitric acid production
F gases	Total	HFCs, PFCs and SF6

4 Simple climate model

The climate model of FAIR 2.0 consists of a global climate submodel (1) and a climate attribution submodel (2).

1. The global climate submodel calculates the greenhouse gas concentrations, temperature increase, rate of temperature increase and sea-level rise for the global emissions scenarios and emission profiles. It also evaluates the indicators using climate targets (see Table 4.1).
2. The climate attribution submodel calculates the regional contributions to different climate change indicators (CO_2 (-equivalent) concentrations, cumulative emissions, radiative forcing, temperature increase and sea-level rise).

The IMAGE-AOS climate model calculates the default global climate. For alternative calculations, either the UNFCCC-ACCC climate model or alternative climate models based on the IRFs derived from simulation experiments with various Atmosphere-Ocean General Circulation Models (AOGCMs) can be used (den Elzen et al., 2002). These models, along with the climate attribution model, will be briefly described below; more details can be found in Appendixes B and C.

Table 4.1. Main climate targets formulated by the European Commission and the Dutch Ministry of Housing, Spatial Planning and the Environment (VROM)

EU	• Global-mean surface temperature increase relative to pre-industrial levels less than 2.0 ^{o}C in the long-term
Dutch ministry:	• Global-mean surface temperature increase relative to pre-industrial levels are less than 2.0 ^{o}C in the long term. • Rate of global temperature increase less than 0.1 ^{o}C per decade • Global-mean sea level rise less than 50 cm in the long term

4.1 IMAGE-AOS climate model

IMAGE 2.2 Atmosphere Oceanic System (IMAGE-AOS) consists of an oceanic carbon, atmospheric chemistry and climate model (Eickhout et al., 2002). The atmospheric CO_2 concentration is calculated using a mass balance equation, with a carbon flux between the atmosphere (and natural vegetation (NEP[16]) as exogenous input, based on data from scenario runs with IMAGE 2.2 (IMAGE-team, 2001). This includes changes in terrestrial uptake resulting from global warming and changes in ambient CO_2 concentration, as well as anthropogenic land use and land cover changes. The oceanic uptake is calculated using the oceanic carbon model, IMAGE 2.2 (Eickhout et al., 2002), i.e. the box-diffusion type model from Joos et al. (1996; 1999); for more details see Appendix B). The atmospheric chemistry model calculates the concentration of the non-CO_2 GHGs using single fixed lifetimes for the atmospheric decay of non-CO_2 gases, except for CH_4, HCFCs and HFCs. For the lifetime of these gases, dependencies on the concentration of the OH radical are included in the methodology on the basis of the IPCC-TAR (Third Assessment Report) methodology of Prather et al. (2001). The default climate model is formed from the Upwelling-Diffusion Climate Model (UDCM) on the basis of the MAGICC model (Hulme et al., 2000; Raper et al., 2001). The main parameters of the IMAGE-AOS climate model are presented in Table 4.2.

[16] NEP - Net Ecosystem Productivity

Table 4.2. Main parameters of the IMAGE-AOS climate model as implemented in the FAIR 2.0 model*

Model parameters	Central value
• Forcing a doubling of CO_2 concentration (in W/m^2)	5.325
• Climate sensitivity parameter, i.e. equilibrium global-mean surface temperature increase resulting from a doubling of CO2-equivalent concentrations (in ^oC)	2.5
• Vertical diffusivity between ocean layers (in cm^2/sec)	2.30
• Upwelling rate at initial steady state (in m/yr)	4
• Temperature change ratio from polar to non-polar region (-)	0.2
• Depth of ocean mixed layer (in m)	60
• Depth of other ocean layers (in m)	100

* See Appendix B for other detailed parameters of IMAGE-AOS.

4.2 UNFCCC-ACCC climate model

One alternative model configuration is specified according to the Terms of Reference of the UNFCCC project entitled 'Assessment of Contributions to Climate Change' (UNFCCC-ACCC).[17] Here, Impulse Response Functions (IRFs) (see Box 1) based on convolution integrals for concentrations, temperature change and sea-level rise are used. There are four four-term CO_2 IRFs included for calculating the CO_2 concentration. Three IRFs are based on three different parameterisations[18] of the Bern Carbon Cycle model in Joos et al. (1996) as applied in the IPCC-TAR (Third Assessment Report), and one IRF on the Bern Carbon Cycle model, as applied in the IPCC-SAR (Second Assessment Report) (Table B.1). The change in concentration of the non-CO_2 GHGs (CH_4, N_2O, HFCs, PFCs, and SF_6) is defined by a single-fixed lifetime expression (Table B.2). For both temperature change and sea-level rise, two-term IRFs were fit to data from a 900-year long experiment using the HadCM3 Coupled General Circulation climate Model (CGCM) (Table B.3).

Table 4.3. Main parameters of the UNFCCC climate model as implemented in the FAIR 2.0 model

• Climate sensitivity parameter, i.e. equilibrium global-mean surface temperature increase resulting from a doubling of the CO_2 equivalent concentrations
• Four IRFs from the Bern Carbon Cycle model (Bern-TAR, Bern-SAR low, Bern-SAR standard, Bern-SAR high) (see Table B.1)

4.3 Alternative climate models

The alternative climate models are based on temperature change IRFs derived from a range of eight AOGCM experiments. Table 4.4 describes the eight IRFs on the basis of AOGCM experiments, i.e.: ECHAM1/LSG (Hasselmann et al., 1993), ECHAM3/LSG (Voss et al., 1998), GFDL '90 (Hasselmann et al., 1993), GFDL '93 2× and GFDL '93 4× (Manabe and Stouffer, 1994), GFDL '97 (Haywood et al., 1997), HadCM2 (Senior and Mitchell, 2000) and CSIRO (Watterson, 2000), as described in den Elzen and Schaeffer (2002). Two other IRFs, based on the IMAGE 2.1 climate model and the Brazilian revised climate model, are also included (Filho and Miguez, 1998). Figure 4.2 shows the response of the IRFs to a

[17] See the UNFCCC website: http://unfccc.int/issues/ccc.html.
[18] Different parameterisations of the CO_2 fertilisation effect.

sudden doubling of CO_2 concentration.[19] Also indicated in Figure 4.2 is the 'outlier' response of the IRFs used in the revised Brazilian Proposal (Filho and Miguez, 1998).

Box 1. What is an Impulse Response Function (IRF)?

IRFs form a simple tool for mathematically describing ('mimic') transient climate model response to external forcing. A two-term IRF model used here (as in Hasselmann et al. , 1993) is based on the following convolution integral, relating temperature response ΔT to time-dependent external forcing $Q(t)$:

$$\Delta T(t) = \frac{\Delta T_{2\times}}{Q_{2\times}} \int_0^t Q(t') \left[\sum_{s=1}^{2} l_s \; (1/\tau_s) \; e^{-(t-t')/\tau_s} \right] dt' \qquad (4.1)$$

where $Q_{2\times}$ is the radiative forcing for a doubling CO_2 and l_s the amplitude of the 1st or 2nd component with exponential adjustment time constant, τ_s, while $l_1 + l_2 = 1$. $\Delta T_{2\times}/Q_{2\times}$ equals the climate sensitivity parameter λ (Cess et al., 1989). In an alternative formulation, we can define $C=1/\lambda$, and characterise C as the *effective* heat capacity of the climate system, including climate-response feedback. An example of IRF performance is seen in Figure 4.1 where results from the CSIRO GCM experiment (Watterson, 2000) and the IRF model are shown using appropriate parameter values. Both models were forced with the same scenario, i.e. the radiative forcing following the IS92a scenario, starting with the historical pathway from 1881 and stabilising at 3 × the present CO_2 concentration (den Elzen and Schaeffer, 2002).

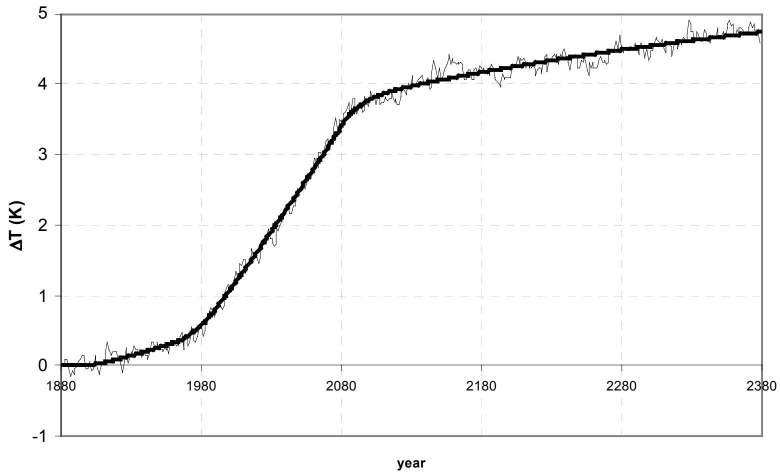

Figure 4.1. The IRF model (heavy line) attuned to the CSIRO GCM data (light line) (Watterson, 2000).

[19] Due to the scenario dependence of IRF fits mentioned above, the IRF responses to this sudden doubling of CO_2 resemble only the 'original' climate model response to such forcing when the same, extreme, scenario was used when determining IRF parameters.

Table 4.4. Parameters for temperature change Impulse Response Functions derived from a range of AOGCM experiments (den Elzen and Schaeffer, 2002)

Climate model	Reference	T_{eq} (°C)	τ_1^T (years)	a_1^T	τ_2^T (years)
ECHAM1/LSG	(Hasselmann et al., 1993)	1.58	2.86	0.685	41.67
ECHAM3/LSG	(Voss et al., 1998)	2.5	14.4	0.761	393
GFDL '90	(Hasselmann et al., 1993)	1.85	1.2	0.473	23.5
GFDL '93 2×	(Manabe and Stouffer, 1994)	3.5	6.5	0.671	388
GFDL '93 4×	(Manabe and Stouffer, 1994)	3.5	8.5	0.665	233
GFDL '97	(Haywood et al., 1997)	3.7	12.6	0.613	145
HadCM2	(Senior and Mitchell, 2000)	3.0	7.4	0.527	199
CSIRO	(Watterson, 2000)	3.6	12.7	0.605	432
IMAGE 2.1	(den Elzen and Schaeffer, 2002)	2.37	2.19	0.654	76
Brazilian revised	(Filho and Miguez, 1998)	3.06	20	0.634	990

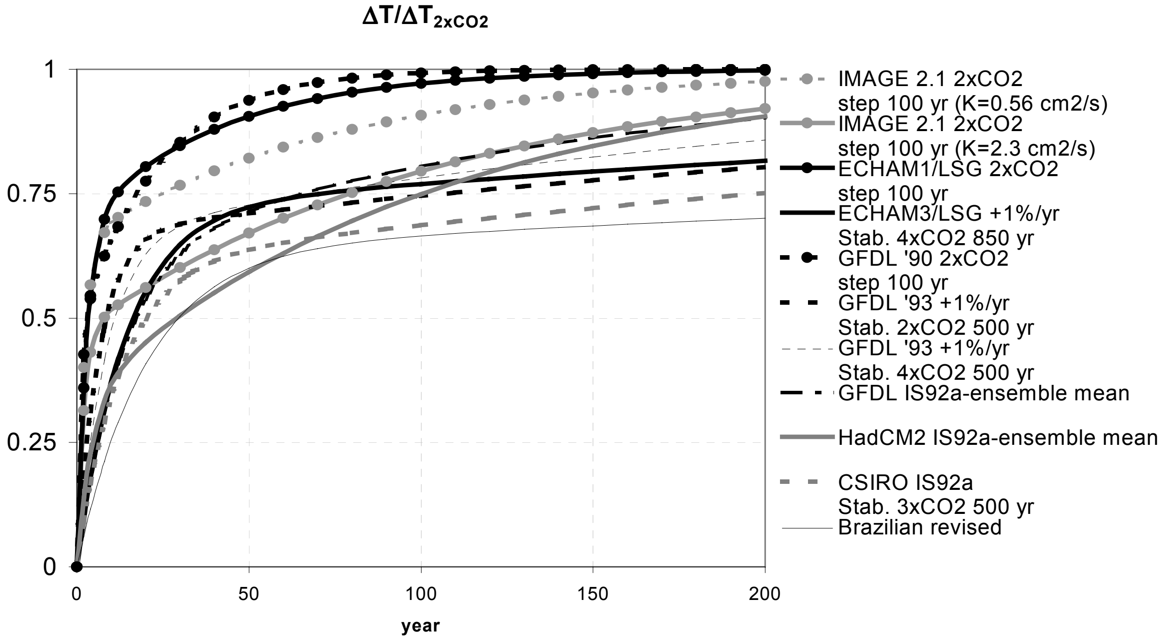

Figure 4.2. The temperature response (normalised by climate sensitivity) to a sudden doubling of the atmospheric CO2 concentration at time t=0 for the various IRFs in Table 4.4 (den Elzen and Schaeffer, 2002).

4.4 Climate attribution submodel

UNFCCC-ACCC and alternative climate models

Contributions of emission regions to climate change indicators like greenhouse gas concentration, radiative forcing, temperature change and sea-level rise are calculated for the UNFCCC-ACCC climate model and the alternative climate models. This is done by separately applying all equations defined at global level to the emissions of the individual emitting regions.[20] Linearity of the equations ensures correct global totals.[21]

[20] The climate attribution model is extensively described in den Elzen et al. (2002).

[21] Only the relationship between concentration and radiative forcing in the UNFCCC-ACCC climate model is non-linear ('saturation effect'). Due to the saturation effect, the radiative forcing of each additional unit of concentration from the 'early emitters' (low saturation of CO_2 absorption) is *larger* than the radiative forcing of an additional unit from the 'later emitters' (higher saturation of CO_2 absorption). Therefore attributing the radiative effects to different regions is not straightforward, e.g. UNFCCC (2002c); see Box 3.

Thus, in this approach the global carbon cycle is divided into *R* hypothetical independent carbon pools, or isolated boxes, one for each emitting region, described by the same C-cycle model and parameters. The global total is simply the linear addition of contributions by all isolated region boxes. We will term this the '*linear approach*' of concentration attribution. Concentrations and removal rates for region *r* in this approach depend only on (anthropogenic) emission (history) of this one region, not on emissions of other regions. In reality, there is only one global carbon cycle.

IMAGE-AOS

The following alternative attribution calculation as applied to the IMAGE-AOS climate attribution model of regional attribution to global CO_2 concentrations appreciates this.

$$\dot{\rho}^r(t) = C_{CO_2} \cdot E^r_{CO_2}(t) - \rho^r(t) / \tau(t) \tag{4.2}$$

with $\tau(t)$ as a time-depending global single 'effective' lifetime, or fairly instantaneous turnover time, of the excess CO_2 mass in the atmosphere. Removal rate in each 'region pool' now depends on global carbon-cycle dynamics, including non-linearity induced by emissions from all regions. An advantage of this method is that global concentrations can be calculated using any (non-linear) carbon-cycle model, like the model in IMAGE-AOS. Non-linearity in the carbon cycle are potentially important. For example, Enting and Law (2002a) showed atmospheric lifetime of CO_2 to increase with higher CO_2 concentration; this can be accounted for using the alternative attribution approach. Here, we will use the IMAGE-AOS model, which, in contrast to the UNFCCC-ACCC carbon cycle model, includes saturation of the CO_2-fertilisation effect over the whole historical and scenario time period. Since IMAGE-AOS further includes scenario-dependant land use changes, it has direct anthropogenic influence on the terrestrial carbon cycle, whereas the UNFCCC-ACCC carbon cycle model represents, in a sense, the natural 'undisturbed' carbon cycle. The effects of using the alternative ('*non-linear' approach,* as described above) to attribute concentrations, and the effect of using a carbon cycle including these non-linearity, is analysed in den Elzen et al. (2002). The methodology of calculating the contributions of emission regions to temperature change and sea level rise within the IMAGE-AOS climate model are described in Appendix C, and is based on earlier work of den Elzen and Schaeffer (den Elzen et al., 1999; den Elzen and Schaeffer, 2002; den Elzen et al., 2002).

Table 4.5. The main parameters of the climate attribution model as implemented in the FAIR 2.0 model

- Starting date of historical emissions (1765-1990)
- Ending date of future emissions (1990-2300)
- Evaluation date of attribution calculations (2000-2300)
- Historical land use emissions (CDIAC or IMAGE-AOS)
- Coverage of GHG emissions (only fossil CO_2 emissions, all anthropogenic CO_2 emissions and all anthropogenic GHG emissions)
- Inclusion or exclusion of non-linearity in the attribution of CO_2 concentration and radiative forcing

Box 3. Modelling the attribution of non-linearity in radiative forcing

Calculating regional contributions to global radiative forcing by a greenhouse gas is now more complicated due to the non-linearity in radiative forcing than contributions to concentration increases and temperature change and sea level rise. There are two possibilities for calculating radiative forcing (Q_g in $W \cdot m^{-2}$) : (i) in proportion to attributed concentrations of a greenhouse gas (the so-called proportional method) or (ii) in proportion to the changes in attributed concentrations (see Appendix C). The first methodology ignores the partial saturation effect and considers equal radiative effects of the 'early' and 'late emitters', whereas the second includes this partial saturation effect, implying a larger radiative effect of the 'early emitters' (Annex I regions). For UNFCC-ACCC, and the IMAGE-AOS climate attribution model, the proportional method (i.e. partitioning the forcing) occurs in the default calculations in proportion to the instantaneous partitioning of the concentrations used, as specified in ACCC-TOR and Appendix C.

Box 4. Modelling the emissions time frame

An important element in the ACCC-TOR methodology is the time frame of the attribution calculations. Variations are possible in the length of the period over which historical emissions are taken into account. In addition, contributions can be calculated for an evaluation date some time after the emission end date, so that future, or delayed, effects are included, as well as the different atmospheric decay rates of the various GHGs. In this way, the climate indicator is 'backward looking' (i.e. takes historical emissions into account), 'backward discounting' (early emissions weigh less depending on the decay in the atmosphere) and 'forward looking' (i.e. takes future effects of the emissions into account) (e.g., Höhne and Harnisch (2002)). This leads to the following three policy choices: (1) a horizon of historical emissions or emission starting date, (2) a horizon of future emissions, or emission end date and (3) evaluation date of attribution calculations.

5 Emission allocation model

The emission allocation model aims at calculating regional emission allowances or assigned amounts (we prefer to call it emission allowances) for various climate regimes for the differentiation of future commitments. The following climate regimes are implemented in the model:
1. Brazilian Proposal (BP)
2. Multi-Stage approach (MS)[22]
3. Per Capita Convergence (PCC)
4. CSE Convergence (CSE)
5. Preference Score approach (PS)
6. Multi-Criteria Convergence (MCC)
7. Emission Intensity Convergence (EIC)
8. Emission Intensity Targets approach (EIT)
9. Jacoby rule approach (JR)
10. Triptych approach (TT).

The following sections comprise short overviews of each regime (or approach), along with the relevant methodology. Before presenting the overviews, however, we will first briefly outline the equity principles and other dimensions of possible regimes for the differentiation of future commitments, with the aim of positioning the various regimes (see Table 5.1).

5.1 Equity principles and other dimensions

Equity principles – Equity principles refer to more general notions or concepts of distributive justice or fairness. Many different categorisations of equity principles can be found in the literature e.g. Ringius et al. (1998; 2002) and, when not contradictory, cannot in general be easily reformulated. To date, a number of key equity principles that have been explored or invoked in the international climate can be identified:

- *Egalitarian:* i.e. all human beings have equal rights in the 'use' of the atmosphere.
- *Sovereignty and acquired rights:* all countries have a right to use the atmosphere, and current emissions constitute a 'status quo right'.
- *Responsibility / polluter pays:* the greater the contribution to the problem, the greater the share of the user in the mitigation / economic burden.
- *Capability:* the greater the capacity to act or ability to pay, the greater the share in the mitigation / economic burden.

The basic needs/no-harm principles are included here as a special expression of the capability principle: the least capable regions should be exempted from the obligation to share in the emission reduction effort so as to secure their basic needs. For a more detailed description please refer to Berk et al. (2002b) and den Elzen et al. (2003b).

The Per Capita Convergence, Multi-Criteria Convergence, CSE Convergence and Preference Score approaches are ultimately based on a combination of the egalitarian and sovereignty principles, while leaving aside the principle of responsibility. The Brazilian Proposal and Jacoby rule are clearly oriented to the responsibility and capability principles, respectively. The Emission Intensity Targets approach is based mainly on capability. However, please note that it is more oriented towards opportunity for mitigation than economic capability. The Multi-Stage approaches (including SMS) are based on a

[22] Including the Simplified Multi-Stage (SMS) approach.

combination of the responsibility and capability principles, but may also include elements related to the egalitarian principle, for example, by using per capita emissions levels as the burden-sharing key. The Triptych approach is based mainly on the capability to act, but also encompasses elements of the egalitarian equity principle.

Other dimensions - In addition to equity principles, there are a number of other dimensions of possible regimes for the differentiation of future commitments, e.g. Berk et al. (2002b).

Problem definition (burden-sharing or resource-sharing. The climate change problem can be defined either as a pollution problem or as a property-sharing issue. These different approaches have implications for the design of climate regimes. In the first approach, burden sharing will focus on defining who should reduce or limit pollution and by how much. In the latter approach the focus is on who has what user rights; the reduction of emissions will be in line with the user rights.

Emission limit. One can define the emission reduction top-down by first defining globally allowed emissions and then applying certain participation and differentiation rules for allocating the overall reduction effort needed. Bottom-up emission reduction is defined by allocating emission control efforts among Parties without a predefined overall emission reduction effort. In the top-down approach, the question of adequacy of commitments is separated from the issue of burden differentiation. In the bottom-up approach, the two are dealt with at the same time.

Participation (thresholds/ timing). Another dimension is the degree of participation: who should participate in sharing the burden and when? This issue concerns discussions on both the types of thresholds for participation and the threshold level or the timing. At the same time, there is no need for all Parties to participate in the same way.

Type of commitment. The approaches for differentiation of commitments can either pre-define the allocations of emissions over time or make the allocation dependent on actual developments in levels of economic activity, population or emissions. In an ex ante analysis this results in baseline-dependent allowance schemes. The level of dependency on actual developments can vary from low, as in the Per Capita Convergence approach (dependent on population only), to high, as in the Multi-Stage approach (dependent on population, income and emissions).

Form of commitment. The form of the commitment may be the same for all countries, such as the binding emission target in the Kyoto Protocol, but may also be defined in a differentiated manner (see e.g. Baumert et al., (1999); Claussen et al., (1998); Philibert and Pershing (2001)). Instead of being fixed absolute targets, commitments may be defined as relative or dynamic targets, such as reduction in energy and/or carbon intensity levels, or in terms of policies and measures. There is also the option of non-binding commitments. In addition, the legal nature of the commitment can be either binding or voluntary.[23]

Scope of the commitment. This dimension is related to the question of whether the commitment covers all GHGs and sectors or is limited to particular GHGs or sectors. Particularly for developing countries, new commitments could be limited to particular sectors

[23] Formally, commitments are always voluntary in the sense that countries voluntarily commit themselves to international agreements. However, a country is formally bound to meet its obligations once ratified. In the case of voluntary commitments there is no formal obligation to achieve a material result (e.g. reduction in emissions).

or GHGs for reasons of verification and monitoring, and because emissions from certain sectors are difficult to predict and control (e.g. agriculture). The present commitments under the KP cover all GHGs and sectors but exclude emissions from international aviation and maritime activities.

Table 5.1 gives a summary of the main characteristics of the ten approaches to international differentiation of future commitments, in terms of the equity principles and other dimensions.

Table 5.1. A comparison of different approaches to international differentiation of future commitments (Berk et al., 2002b; den Elzen et al., 2003b)

Dimensions	BP	MS	PCC/ CSE	PS	MCC	EIC	EIT	JR	TT
Equity principles									
1. *Responsibility*	X	X							
2. *Capability*	(X)	X	(X)			X	X	X	X
3. *Egalitarian*		X	X	X	X				X
4. *Sovereignty*			X	X	X	X	(X)		
Problem definition									
• *Pollution problem*	X	X					X	X	X
• *Global commons issue*			X	X	X	X			
Emissions limit									
• *Top down*	X	X	X	X	X	X		(X)	
• *Bottom up*							X	X	X
Participation									
• *Partial*	X	X					X	X	
• *All*			X	X	X	X			X
Nature of Commitment									
• *Pre-defined*			X	X	X				
• *Path- dependent*	X	X				X	X	X	X
Form of Commitment									
• *Equal*	X		X	X	X	X	X	X	X
• *Differentiated*		X							X
Scope of the Commitment									
• *Full coverage*	X	X	X	X	X	X	X	X	X
• *Partial coverage (of sector per /GHGs)*		(X)							

X= applicable; (X) = partly applicable

The PCC, CSE and PS approaches are the only ones based on the global commons paradigm and resource-sharing concept; the other approaches are based on the pollution problem paradigm and burden-sharing concept. Only the Jacoby Rule, Triptych and EIT are based on a bottom-up approach. None of the approaches include limitations in the scope of the commitments (full coverage of GHGs and sectors), although in practice the intensity targets of the MS approach could be restricted to some gases or sectors. All approaches are comprehensive in the sense that all countries' commitments are governed by the regime, except for the Multi-Stage, Brazilian Proposal, Jacoby Rule and EIT approaches, which include a threshold for effective participation. The PCC and PS approaches pre-define the (share in) allocation of emissions, largely irrespective of future developments apart from population. In the ex-ante analysis, emission allocations in the Multi-Stage, Jacoby rule and Triptych approaches are most strongly influenced by baseline projections of income and emission levels. The Multi-Stage approach is the only approach that incorporates different forms of commitments (e.g. de-carbonisation or intensity targets in addition to fixed emission stabilisation and reduction targets).

5.2 Brazilian Proposal

During the negotiations on the Kyoto Protocol, the Brazil delegation presented an approach for distributing the burden of emission reductions among Annex I Parties. This was based on the effect of their cumulative historical emissions (from 1840) on the global average surface temperature (UNFCCC, 1997a). Although this proposal was initially developed to support discussion on the differentiation of future commitments among Annex I countries, it can also be used as a framework for discussions between Annex I and non-Annex I countries on future participation by all countries in emission reductions. The Brazilian Proposal was not adopted but did receive support, especially from developing countries. To keep this concept on the agenda, the Third Conference of the Parties (COP-3) decided to ask the Subsidiary Body on Scientific and Technical Advice (SBSTA) of the UNFCCC to further study the methodological and scientific aspects of the proposal.[24]

In 2002, the UNFCCC secretariat organised a co-ordinated modelling exercise amongst research institutions active in the field of climate change to assess the contributions to climate change. This UNFCCC project is entitled 'Assessment of Contributions to Climate Change' (UNFCCC-ACCC) (UNFCCC, 2002a), with its main findings reported in UNFCCC (2002b). So far, this 'Brazilian Proposal' is the only climate regime that has been formally discussed and documented within the UNFCCC. The proposal was studied by RIVM (den Elzen et al., 1999; den Elzen and Schaeffer, 2002) and, recently, in the UNFCCC-ACCC (den Elzen et al., 2002).

Table 5.2. Main characteristics of the Brazilian Proposal approach.

- Focus on responsibility principle
- Top-down approach
- Partial participation
- The same form of commitments (contribution to temperature increase)
- Share of the global emission reduction

Methodology – Here, the Brazilian Proposal is applied on a global scale, with an income threshold for participation for the non-Annex I regions. The allocations of emission reductions is also not only based on the contribution to temperature increase, but could also be based on contributions to other global climate change indicators, such as cumulative emissions, concentrations, etc. For the contribution calculations we use the UNFCCC climate attribution methodology, as implemented in the climate attribution model (see Chapter 4). The income threshold for participation is chosen as a percentage of the1990 PPP-Annex I per capita income. This percentage is selected on the basis of the following criteria: (i) feasibility under the emission profile; (ii) timely participation of the non-Annex I regions and (iii) avoidance of disproportional burdens, i.e. negative emission allowances.[25] To achieve timely participation of some low-income non-Annex I regions, i.e. South Africa and South Asia , an additional threshold of a proportion of world average per capita emission levels is also included (den Elzen et al., 2003c). The participation of the low-income non-Annex I countries as above is necessary to achieve the emission profile

[24] See also the UNFCCC website (http://unfccc.int/issues/ccc.html).

[25] Negative emission allowances indicate that a region's emission reduction obligation resulting from its share in the burden-sharing key and the total global emissions reduction burden exceeds its remaining emission allowances from the previous commitment period. For the Brazilian Proposal this takes place under a stringent global emission constraint. Due to their large historical contributions to temperature change, the share of some Annex I regions - notably Europe - in the overall emission burden decreases less rapidly than their share in total emission allowances over time.

and avoid disproportional burdens for some Annex I regions, i.e. OECD Europe and Japan, with large contributions to global temperature increase.

Policy choices[26] as well as scientific uncertainties play a role in the calculation of the regional contribution to temperature increase. More specifically, policy choices, which can be explored are in BP, are, for example, (i) the choice of other climate indicators than temperature increase, (ii) the time horizon of emissions, i.e. horizon of historical emissions, or emission starting date, horizon of future emissions, emission end date and evaluation date of attribution calculations (see Box 4) and (iii) the choice of the mixture of greenhouse gases (GHG).

The scientific uncertainties explored here include: (iv) non-linearities in the cause-and-effect chain of climate change, i.e. non-linearities in concentration and radiative forcing attribution (the linear and non-linear attribution approach as described in section 4.4 and Box 3), (v) using alternative carbon cycle, atmospheric chemistry and climate models (see sections 4.1-4.3) and (vi) alternative historical emission datasets (section 4.1). Recent research has shown that the impact of policy choices on individual country contributions is much larger than that of the scientific uncertainties analysed so far (den Elzen and Schaeffer, 2002; den Elzen et al., 2002). Also the impact of scientific uncertainties will, though limited, be compared to policy choices, to apply the Brazilian Proposal as a climate regime for differentiation of commitments. Here, we consider only the policy choices as important. Analyses of the Brazilian Proposal approach are presented in den Elzen et al. (2003b; 1999; 2003c).

Table 5.3. Main policy parameters of the Brazilian Proposal approach

- Time horizon emissions: (a) starting date historical emissions (1765-1990), and (b) end date future emissions (2000-2100)
- Participation threshold: (a) income threshold in %-Annex I per capita income in PPP$ or US$ per capita.yr, and/or (b) emission threshold in %-world average per capita emission levels
- Differentiation of commitments based on contribution to different climate indicators, i.e. global temperature increase or other climate indicators (cumulative emissions, concentrations, radiative forcing and sea level rise, etc.)

5.3 Multi-Stage approach

The Multi-Stage approach is basically a system for a gradual extension of the group of countries taking on quantified emission limitations and reduction objectives and deepening of their commitments over time. More specifically, the Multi-Stage approach consists of a system to divide countries into groups with different levels of responsibility or types of commitments (stages). This results in a system that divides regions into groups with different levels of commitments (stages). The aim of such a system is to ensure that regions with similar circumstances in economic, developmental and environmental terms have comparable responsibilities / commitments under the climate regime. Moreover, the system

[26] The term 'policy choice' refers to variables in the calculation, the values of which can not be based on objective ('scientific') arguments alone. As an analogy, consider the use of a time horizon of 100 years for GWPs, as decided within UNFCCC. Choosing a different time horizon has disadvantages and advantages, depending on the question at hand. The decision of which time horizon to use requires a certain level of expert knowledge, but is ultimately a political choice. Although increasing scientific knowledge and decreasing scientific uncertainty might shed more light on the consequences of such policy choices, the choices themselves will thus always have to be made, largely within the policy context.

defines when a country's level of commitment changes according to pre-determined rules related to a change in its circumstances.

The Multi-Stage approach thus results in an incremental evolution of the climate regime, i.e. a gradual expansion over time of the group of countries with (mitigation) commitments (Annex I), with countries adopting different levels and types of commitments according to participation and differentiation rules. The various levels of participation could be organised as different Annexes to the UNFCCC. The approach was first developed by Gupta (1998). Later the approach was elaborated into a quantitative scheme compatible with the UNFCCC objective of stabilising the atmospheric greenhouse gas concentrations at a level that would *'prevent dangerous anthropogenic interference with the climate system'*. This has be done by den Elzen et al. (1999), Berk and den Elzen (2001) and den Elzen (2002).

In order to enhance the realism of the Multi-Stage approach there are two new elements included: (i) accounting for policy delay between trespassing any threshold and taking action in the first sequential commitment period (policy delay) and (ii) using a reference period for threshold levels (reference period). See Appendix D (den Elzen et al., 2003a).

Table 5.4. Main characteristics of the Multi-Stage approach

- Focus on capability and responsibility principle
- Top-down approach
- Partial participation
- Differentiated form of commitment (stages)
- Different participation thresholds
- Share of the global emission reduction

Methodology - The Multi-Stage approach is based on four consecutive stages for the commitments of non-Annex I regions beyond 2012, i.e.:

- *Stage 1. No quantitative commitments*. Non-Annex I regions follow their baseline emissions until they meet the *first participation threshold* based on income and/or emissions or a pre-selected starting year, after which they switch to the second stage.
- *Stage 2. Adoption of intensity targets*. The non-Annex I regions then adopt *intensity improvement targets*, defined by the rate of reduction in the emission intensity of their economies (GHG emissions per unit of economic activity expressed in PPP$ or US$ terms) until they reach the *second participation threshold*.
- *Stage 3. Stabilisation of emissions***.** The non-Annex I regions then enter an emission stabilisation period, in which they stabilise their emissions[27] for a number of years before actually entering the emissions reduction regime.
- *Stage 4. Emission reduction targets*. Here the total reduction effort[28] to achieve the global emission profile is shared amongst all participating regions on the basis of a burden-sharing key[29] (for example, per capita emissions[30]).

[27] It is also possible to stabilise the per capita emissions instead of the total emissions.
[28] The difference in the remaining emissions, i.e. profile emissions minus region emissions in stages 1, 2 and 3, at times t and t-1.
[29] The following burden-sharing keys are included: CO_2-equivalent emissions, cumulated CO_2-equivalent emissions, CO_2-equivalent emissions per capita (population scenario), CO_2-equivalent emissions per capita (with population cap), CO_2 concentration, CO_2-equivalent concentration, global temperature increase, sea-level rise, CO_2 concentration per capita, CO_2-equivalent concentration per capita, temperature increase per capita, sea-level rise per capita, CO_2 concentration per capita (cap population), radiative forcing or CO_2-equivalent concentration per capita (cap population), temperature increase per capita (cap population), sea-

It is assumed that all Annex I regions (including the US) are found in stage 4 after 2012.

First participation threshold – The first participation threshold for stage 2 could be a fixed income threshold, a dynamic emission threshold or a fixed starting year. Its value depends on the stringency of the emission profile. A low threshold value would lead to an early participation of low-income countries, which has several advantages: (1) fast expansion of the global emission trading market; (2) less leakage to non-participating countries; (3) more spillover of technology and (4) more flexibility in adjusting to possible more stringent future climate targets.

Intensity improvement target - Early adoption of intensity targets can be made attractive when related to per capita income levels (very small efforts and emission-trading gains). Therefore the GHG emission intensity improvement rate [$EIR_R(t)$] is defined as a linear function of per capita income level (*IC* in US$ or PPP$ per capita), i.e.:

$$EIR_R(t) = \quad max\ [\ a*IC_R(t),\ EIR_{max}] \qquad (5.1)$$

where t is the year of calculation, a, a coefficient and EIR_{max}, the maximum de-carbonisation rate. The latter is adopted to avoid de-carbonisation rates that would outpace those of economic growth and would result in absolute reduction targets for middle-income countries. The basic idea behind the coefficient a is that the rate reaches a maximum at a certain percentage of 1990 Annex I income (e.g. 3% at 40% of 1990-Annex I income, where the corresponding income level is IC_{max} in US$ or PPP$ per capita) and can be calculated as EIR_{max} / IC_{max}.

Another income-differentiated de-carbonisation target implemented in the FAIR 2.0 model is based on different time-dependent improvement rates for income groups of countries (hereafter known as income-group-dependent intensity targets) (den Elzen, 2002). For the high-income regions (more than 5000 PPP$ per capita) a constant de-carbonisation target of 2.5% per year is assumed. The middle-income regions (2500-5000 PPP$ per capita) start with a target of 1% per year after 2010, which increases linearly up to 2.5% per year by 2030. The low-income regions (less than 2500 PPP$ per capita) start with a target of 0.5% per year after 2010, which increases up to 2.5% per year by 2050.[31]

Second participation threshold – Similar to the first participation threshold, there are basically two options: an income threshold and/or a dynamic emission threshold. A dynamic emission threshold such as percentage of world average per capita emissions accommodates the change over time in the world average per capita emission levels. This has two advantages: (1) it ensures timely participation of developing countries to keep total emissions below a global emission ceiling for meeting stabilisation targets and (2) it rewards Annex I action since this brings the threshold level down.

Analyses of the Multi-Stage approach are presented in den Elzen et al. (1999), Berk and den Elzen (2001), den Elzen (2002) and den Elzen et al. (2003b). Box 5 (below) describes the more simplified Multi-Stage approach, e.g. den Elzen et al. (2003a), with fewer stage and policy parameters.

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level rise per capita (cap population), emission intensity (in gC/US$ or gC/PPP$), Gross Domestic Product (US$) and Gross Domestic Product per capita (US$ per capita or PPP$ per capita x year).

[30] The share of a region r in the total emission reduction is calculated as: $X_r = (E_r * pcE_r)$ divided by the sum of X_r over all regions, with E_r the total emissions and pcE_r the per capita emissions. In this way, two regions with equal per capita emissions, but different total emissions, have the same relative reduction effort compared to their emissions.

[31] Other implemented intensity targets include user-defined improvement rates, i.e. an equal or differentiated rate for all non-Annex I regions.

Box 5. Simplified Multi-Stage approach

Den Elzen et al. (2003a) have simplified the original Multi-Stage approach, since it was felt that a simplification of the approach would make it more easily assessable. For this reason they suggested reducing the number of stages and policy variables, leading to a new, more simplified, Multi-Stage approach.

Methodology – The approach has resulted in three distinct Multi-Stage cases (MS1, MS2 and MS3), that all have several features in common but differ in other aspects. More specifically, the three Multi-Stage cases are based on the same definition of the three consecutive stages for the commitments of non-Annex I regions beyond 2012, i.e.:

- *Stage 1. No quantitative commitments*. Non-Annex I regions follow their baseline emissions.
- *Stage 2. Emission (growth) limitation targets*. The non-Annex I regions then adopt intensity improvement targets (Multi-Stage 1, Multi-Stage 2), or follow a prescribed slowdown in the emission growth to a final stabilisation (Multi-Stage 3).
- *Stage 3. Emission reduction targets*. Here the total reduction effort to achieve the global emission profile is shared among all participating regions on the basis of a burden-sharing key (here, per capita emissions).[32]

All Annex I regions (including the US) are assumed to be in stage 3 after 2012. The different thresholds or transition process are defined below (Table 5.6).

From Stage 1 to Stage 2 - The transition of a region from Stage 1 to Stage 2 depends, for all MS variants considered here, on a Capacity-Responsibility (CR) index. The CR index is, in practical terms, defined as the sum of the per capita income (in 1000PPP$ per capita), which relates to the capacity to act, and the per capita CO_2-equivalent emissions (in tCO_2 per capita), which reflects the responsibility in climate change.[33]

Stage 2 - In Stage 2 the MS1 and MS2 cases share income-related intensity targets, i.e. GHG intensity improvement targets based on the same income-dependent relationship as adopted under the intensity stage of Multi-Stage (equation 5.1). The MS3 case assumes prescribed emission limitation growth targets for stage 2, leading to a stabilisation of emissions as in the Soft-Landing approach. The length of this stabilisation period is given by the transition constant TC and is calculated by dividing the TC by the per capita emission levels (in tCO_2 per capita) before the first CR threshold is met. For example, if the transition constant is 70, a region with per capita emission levels of 5 tCO_2 per capita will have to bring down its emission growth rate to zero in 14 years.

From Stage 2 to Stage 3 - The three MS cases differ only with respect to the transition from Stage 2 to Stage 3, i.e. from dynamic emission (growth) limitation targets to absolute emission reduction targets. In MS1 the entry to Stage 3 depends on a threshold defined as a proportion of the world average per capita emission level. MS2 uses the CR index, with a value that is about twice that used for the Stage 1 to Stage 2 threshold. In MS3 the entry to Stage 3 begins after the end of the period that allows for a progressive linear reduction from the initial emission growth rates to zero.[34]

[32] Den Elzen et al. (2003a) have also analysed burden-sharing keys, such as per capita income, total emissions, etc.

[33] A weighting factor can be included if necessary. A proper weighting of both C and R can prevent too poor countries having to participate early onwards. No weighting is included in the default calculations.

[34] The emissions during stage 2 are calculated as: $E(t-1)+V_0*\{1-[(t-t_0)/LTS]\}$, where E(t-1) represents the emissions of the previous year, t_0 the starting year, LTS the length of the stabilisation period and V_0 the average increase in the emissions before the CR threshold is passed.

Box 5 (continued)

Table 5.5. The main characteristics of the three simplified Multi-Stage cases

	MS1	MS2	MS3
Stage 1 No quantitative commitments			
Stage 2 (emission-limitation stage)			
First threshold (to stage 2)	CR index	Same as MS1	Same as MS1
Emission-limitation targets	Income-dependent intensity targets	Same as MS1	Prescribed emission stabilisation profile
Stage 3 (emission-reduction stage)			
Second threshold (to stage 3)	%-world average per capita emissions	CR index	--
Absolute targets, reductions proportional to burden-sharing key	Per capita emissions	Same as MS1	Same as MS1

Table 5.6. Main policy parameters of the simplified Multi-Stage approach

- First participation threshold (Stage 1): Capability-Responsibility (CR) index value
- Second participation threshold (Stage 2): %-world average per capita emissions (MS1), CR index value (MS2), TC value (related to the length of the stabilisation period) (MS3).
- Income-dependent intensity targets (maximum de-carbonisation rate, coefficient *a*)
- Policy delay (time delay between achieving threshold and taking action)
- Reference period (time period of commitment period)

Table 5.7. Main policy parameters of the Multi-Stage approach

- First participation threshold (Stage 1): (a) income threshold in %-1990 Annex I per capita income in PPP$ or US$ per capita x year, or (b) emission threshold in %-world emissions per capita, or (c) starting year
- Second participation threshold (Stage 2): (a) income threshold in %-1990 Annex I per capita income in PPP$ or US$ per capita x year, and/or (b) emission threshold (% of world average per capita emissions)
- Intensity targets in Stage 2: (a) income-dependent intensity targets (maximum de-carbonisation rate, coefficient *a*), or (b) income-group-dependent intensity targets (improvement rates for different income groups) or (c) user-defined targets (equal or a differentiated rate)
- Stabilisation period of emissions for Stage 3 (years)
- Differentiation of commitments for Stage 4 based on contribution to emissions, per capita emissions, per capita income (in PPP$ or US$ per capita x year), emission intensity, temperature increase, etc.
- Policy delay (time delay between achieving threshold and taking action)
- Reference period (time period of commitment period)

5.4 Per Capita Convergence approach

An alternative approach that would represent a major shift from the present protocol approach is the so-called ‘Contraction & Convergence’ (C&C) approach of the Global Common Institute (GCI) (Meyer, 2000)[35], or as we prefer to call it, the Per Capita Convergence (PCC) approach. Instead of focusing on the question of how to share the emission reduction burden, this PCC approach starts from the assumption that the atmosphere is a global common to which all are equally entitled. It defines emission rights

[35] The website can be found via http://www.gci.org.uk.

on the basis of a convergence of per capita emissions under a contracting global emission profile. In the PCC approach all regions participate immediately in the emission-control regime (in the post-Kyoto period), with per capita emission rights/permits converging towards equal levels over time. The top-down PCC approach is a combination of sovereignty/status quo rights and the needs or egalitarian equity principle. It leaves aside differences in historical contributions to the problem.

Table 5.8. Main characteristics of the Per Capita Convergence approach

- Focus on egalitarian and sovereignty principle
- Top-down approach
- Global participation
- Equal form of commitments
- Share of the global emissions on the basis of convergence in per capita emissions

Methodology - The regime uses a format similar to the Multi-Stage approach, and a global atmospheric greenhouse gas concentration target is selected, which creates a long-term global emission profile or global GHG emission contraction budget. This budget is then allocated to the regions/countries so as to have the per-capita emissions converge from their individual values to a global average. More specifically, all shares converge from actual proportions in emissions to shares based on the distribution of population in the convergence year. For the original convergence approach[36] of the GCI, a non-linear convergence, the actual degree of convergence in per capita emissions allocated each year depends on the rate of convergence selected. The rate of convergence determines whether most of the per capita convergence takes place at the beginning or near the end of the convergence period. The higher the value for the rate of convergence, the more the convergence takes place towards the end of the convergence period and vice-versa. The default value in the GCI contraction & convergence cases is 4, leading to a balance in the convergence. In the meantime, GCI has indicated that the non-linear convergence method is not an essential element of the C&C approach and that a linear approach may be adopted as well. The linear convergence equation is:

$$S_r\,(t) = S_r(t_{start}).(1-\tau) + \; P_r(t).\tau\,, \tag{5.2}$$

where $S_r(t)$ is the emission share (%) at time t, $P_r(t)$ the population share at time t, and τ the time ratio ($\tau = 0$ at the start of the convergence t_{start} (here: 2010) and $\tau = 1$ at chosen convergence year.

Another key parameter in the approach is accounting for population growth, which could discourage population control. For this reason, the approach may be combined with the option of applying a cut-off year after which population growth is no longer accounted for. Applying a cut-off year for population means that the population share in calculating convergence is kept constant after this year. Note that there is no assumption made about what populations will or should be beyond the cut-off year; merely that population growth after that year should not accrue additional emission rights.

Analyses of the Per Capita Convergence approach are presented in den Elzen et al. (1999), Berk and den Elzen (2001), den Elzen (2002) and den Elzen et al. (2003b).

[36] The equation for non-linear convergence is: $S_r\,(t) = S_r(t\text{ -1}) - [S_r(t\text{ -1}) - P_r(t\text{ -1})].\exp\,[-\alpha.(1-\tau)]$, where $S_r(t)$ is the emission share (%) at time t, $P_r(t)$ the population share at time t, α the convergence rate coefficient and τ the time ratio ($\tau = 0$ at the start of the convergence t_{start} (here: 2010) and $\tau = 1$ at chosen convergence year).

Table 5.9. Main policy parameters of the Per Capita Convergence approach

- Convergence year
- Type of convergence: (a) linear convergence, or (b) non-linear convergence (rate of convergence, i.e. coefficient α).
- Cap on population (including, or excluding)

5.5 CSE Convergence

The Centre of Science and Environment (CSE) in India also supports the Contraction & Convergence concept (CSE, 1998) but has suggested a variant in which the concept is combined with basic sustainable emission rights. The latter is related to the idea of both survival emissions and common emissions, e.g. natural sink for CO_2 (in particular, the oceans) (Agarwal et al., 1999; Agarwal and Narain, 1991; CSE, 1998).

In the CSE convergence this global sustainable emission level is related to the amount of CO_2 emission that can be emitted in the very long term without raising the atmospheric concentrations due to carbon sequestered by natural sinks (in particular, oceans). This is the ultimate level for stabilisation of CO_2 concentrations, as referred to in Article 2 of the UNFCC (UNFCCC, 1992).[37]

Table 5.10. Main characteristics of the CSE Convergence approach

- Focus on egalitarian and sovereignty principle
- Top-down approach
- Global participation
- Equal form of commitments
- Basic emission rights related to a global ‘sustainable’ emission level
- Share of the ‘remaining’ emissions on the basis of convergence in per capita emissions

Methodology – This global ‘sustainable emission level’ is allocated to all regions on a per capita basis, as a common goal using the equity principle: *every human being in future has a basic emission quotum irrespective of the country where he or she lives.* Given future population development, this basic per capita emission quotum changes in time, and is simply calculated as the global ‘sustainable’ emission level divided by the population size. Besides this basic emission quotum, each human being has a remaining emission quotum, which is calculated using the linear convergence methodology (see section 5.4), but now using a ‘remaining’ global emission profile. This remaining global emissions profile is determined by the global emission profile minus the global ‘sustainable’ emission level (see also CSE, 1998). The CSE convergence can also be applied with a cap on population.

Table 5.11. Main policy parameters of the CSE Convergence approach as implemented in the FAIR 2.0 model

- Convergence year
- Global ‘sustainable emission level’
- Cap on population (including, or excluding such a cap)

5.6 Preference Score approach

This Preference Score (PS) approach is based on the Preference Score method, which can be used to ascertain consensus in a multi-base distribution. To solve conflicts between Parties, the

[37] Here we apply this level to all GHGs.

Preference Score method creates a weighted, arithmetic mean for base proposals and Party preferences. For the Preference Score, consensus is sought in a doubled-based - population and emissions - distribution proposal on sharing global emission allowances. More specifically, in the Preference Score approach, the allocation of global emissions is based on a population-weighted preference for emissions or population distributions. The approach is based on resource sharing, not on burden sharing.

Table 5.12. Main characteristics of the Preference Score approach

- Focus on egalitarian and sovereignty principle
- Top-down approach
- Global participation
- Equal form of commitments
- Share of the global emissions based on population-weighted preference for emissions or population distributions

Methodology - Since a participation threshold is not used, all regions join the emission allocation regime immediately after the Kyoto period. The calculation of the regional emission allowances takes place in two steps: the voting step, followed by an allocation of emissions on the basis of a population-weighted averaging of the preferences. In the voting step, each region determines its preferred (=most favourable) distribution method (per capita or grandfathering). Weight factors for grandfathering (α) and per capita allocation (β) are determined on the basis of the total share of the world population in favour of each method. Next, the emission shares per region (S_R) are calculated as follows as the (population-)weighted mean between the population (PC) and grandfathering (GF) shares using the calculated weights:

$$S_R(t) = \alpha(t_{ref}).GF(t_{ref}) + \beta(t_{ref}).PC(t_{ref}), \qquad (5.3)$$

where t is the year of calculation. The calculation of the shares is dependent on the policy delay assumed (pd). This policy delay is used to calculate the reference year ($t_{ref} = t - pd$), which is the year from which the data are used to calculate the emission shares and weights. The absolute allowable emissions are dependent on the global emission profile.

An analysis of the PS approach is presented in den Elzen et al. (2003b).

Table 5.13. Main policy parameters of the Preference Score approach

- Policy delay
- Cap on population (including, or excluding)

5.7 Multi-criteria approach

A variant of the Per Capita Convergence is the Multi-criteria convergence, but now converging to a multi-criteria index. This is based on a weighting of three indicators (GHG emissions per capita, emission intensity and emissions) in which each indicator is given equal weight (1/3), with the sum of these weights equal to 1 (den Elzen and Berk, 2003a).

Methodology – The equation for this convergence is given by:

$$S_r(t) = S_r(t_{start}).(1-\tau) + [1/3 * P_r(t) + 1/3 * GDP_r(t) + 1/3 * EM_r(t)].\tau, \qquad (5.4)$$

where $S_r(t)$ is the emission share (%) at time t, $P_r(t)$, $GDP_r(t)$ and $EM_r(t)$ the share of population, GDP and emissions at time t, and τ the time ratio ($\tau = 0$ at the start of the convergence t_{start} (here: 2010) and $\tau = 1$ at chosen convergence year.

Table 5.14. Main characteristics of the Multi-Criteria Convergence approach

- Focus on egalitarian and sovereignty principle
- Top-down approach
- Global participation
- Equal form of commitments
- Share of the global emissions based on a weighting of three indicators, i.e. GHG emissions per capita, emission intensity and emissions

Figure 5.1 illustrates the sensitivity of the emission allowances to the weighting factors for the Annex I and non-Annex I regions relative to their 1990 levels. Three alternative cases are shown here, each with the resource-sharing key based solely on one of the three factors, representing the approaches: per capita convergence, convergence in emission intensity and grandfathering. Grandfathering evidently leads to the lowest emission reductions of all Annex I regions, whereas convergence in the emission intensity gives the lowest reductions for OECD regions, in particular EU enlarged and Japan (see also next section). Per Capita convergence has the highest emission allowances for the low-income non-Annex I regions.

An analysis of the Multi-Criteria Convergence approach is presented in den Elzen and Berk (2003a).

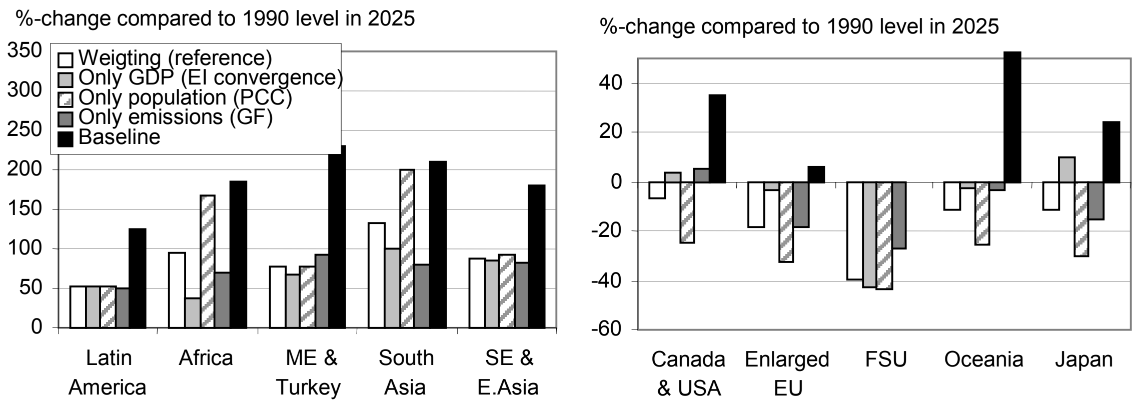

Figure 5.1. Sensitivity to weighting factors for the Multi-criteria convergence approach. Percentage change in the emission allowances for the S550e profile for the Annex I and non-Annex I regions in 2025 is shown relative to the 1990 levels .

5.8 Emission Intensity Convergence approach

The Emission Intensity Convergence (EIC) approach is basically the same as the Per Capita Convergence approach, except that it now defines emission rights on the basis of a convergence of emissions intensities under a contracting global emission profile. In the Emission Intensity Convergence approach all regions participate immediately in the climate regime (in the post-Kyoto period), with emission intensities (in gC/US$, or gC/PPP$)) converging over time to equal levels.

Methodology – More specifically, all shares converge linearly over time from actual proportions in emissions to shares based on the distribution of GDP (in US$ or PPP$) in the convergence year.

Table 5.15. Main characteristics of the Emission Intensity Convergence approach as implemented in the FAIR 2.0 model

- Focus on capability principle
- Top-down approach
- Global participation
- Equal form of commitments
- Share of the global emissions on the basis of convergence in GHG emission intensity

Table 5.16. Main policy parameters of the Emission Intensity Convergence approach as implemented in the FAIR 2.0 model

- Convergence year
- GHG emission intensity in (gC/US$, or gC/PPP$)

5.9 Emission Intensity Targets approach

The Emission Intensity Targets (EIT) approach is bottom-up. Basically, it assumes that all regions adopt GHG intensity targets directly after Kyoto upon reaching a certain income threshold (den Elzen and Berk, 2003b). This threshold has been adopted to derive a gradual expansion over time of the group of countries with intensity targets and is therefore somewhat similar to the first participation threshold in the Multi-Stage approach.

Methodology – The GHG intensity improvement target is again based on the same income-dependent relationship as adopted under the intensity stage of the Multi-Stage approach (equation 5.1). However, since this relationship is now also adopted for all Annex I regions, a modification of assumed maximum de-carbonisation rates is needed. Western Europe and Japan, both OECD regions that are already relatively efficient and therefore do not lend themselves to much improvement, are assumed to improve at a rate of 50% of the maximum rate. For the emission intensity level, it is assumed that *all* other regions will ultimately converge to the level of these - most efficient - regions and then follow rate of improvements. This stimulates creation of a technological frontier and the dynamics of the 'catching-up' process with reference to this frontier. Figure 5.2 illustrates this process for the IMAGE S650e profile with respect to the baseline IMAGE A2 emission scenario.

In the default calculations this approach also assumes that 50% higher maximum de-carbonisation rate for the FSU, since the emission intensity of this region is much higher compared to the other regions. Figure 5.2 also shows the decrease in the GHG emission intensities starting from 1970, and clearly shows the convergence in the emission intensity between the US and SE & East Asia (China). The figure also shows that the non-Annex I emission intensities tend to converge towards the technological frontiers, but actual convergence is not achieved before 2050.

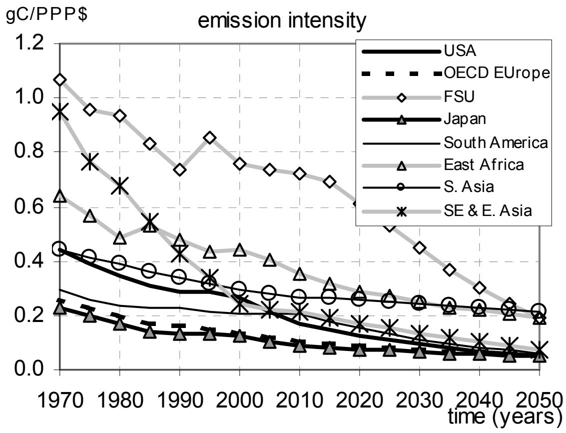

Figure 5.2. Emission intensity of several selected regions for the S650e global emission profile, aiming at a stabilisation of CO_2-equivalent concentration at 650 ppmv (den Elzen and Berk, 2003b).

To make the results of this bottom-up approach comparable to that of the other top-down approaches, it is possible to attune the overall stringency of the commitments with different values to the maximum de-carbonisation rate and to attune the income threshold so that the cumulative emissions for this century are comparable to those under the emission profiles.[38]

An analysis of the Emission Intensity Targets approach is presented in den Elzen and Berk (2003b).

Table 5.17. Main characteristics of the Emission Intensity Targets approach as implemented in the FAIR 2.0 model

- Focus on capability principle
- Bottom-up approach
- Partial participation
- Equal form of commitments (emission intensity improvement rates)

Table 5.18. Main policy parameters of the Emission Intensity Targets approach as implemented in the FAIR 2.0 model

- Income-dependent intensity targets (maximum de-carbonisation rate, coefficient *a*)
- Modification factors of the maximum de-carbonisation rate for particular regions (i.e. Western Europe, Japan and FSU)
- Participation threshold: income threshold in %-1990 Annex I per capita income in PPP$ or US$ per capita x year
- GHG emission intensity in gC/US$, or gC/PPP$

5.10 Jacoby Rule approach

A more bottom-up approach for burden-sharing is the so-called 'Jacoby rule', introduced by Jacoby et al. (1999) as an illustrative model of accession and burden-sharing. The basic principle behind this approach is the ability to pay. In comparison to the other approaches analysed here, the regional emission allowances are not calculated by sharing the emission space of the global emission target profile using pre-defined burden-sharing rules, but by

[38] For the higher economic growth scenarios, for example, the IMAGE A1b scenario, this will evidently require higher values of the maximum de-carbonisation rate.

applying a mathematical equation to calculate the emission allowances. The basis of this equation is that Parties only enter the international climate regime (and reduce their emissions) once they have exceeded a level of per capita welfare (a welfare 'trigger'); otherwise they will follow their reference emissions (unconstrained no-policy emission trajectory). The emission reduction is calculated on the basis of the difference between the per capita welfare income trigger level and a region's per capita welfare.

Table 5.19. Main characteristics of the Jacoby rule approach

- Focus on capability principle
- Bottom-up approach (can also be applied top-down by scaling towards emission profile)
- Partial participation
- Equal form of commitments
- Share of the global emission reduction based on per capita income

Methodology - The most important variable in this regime is the per capita welfare trigger. This trigger allows regions to commit themselves to joining the emission reduction scheme. The emission reduction rate of region r at time t [$\eta_r(t)$] is then calculated using the difference between the welfare trigger (per capita income) (w^* in PPP$ per capita per year) and the per capita welfare of the previous time-step, $w_r(t-1)$:

$$\eta_r(t) = \gamma - \alpha.[w_r(t-1)-w^*]^\beta \qquad (5.4)$$

Using this equation, the emission allowance of region r at time t [$E_r(t)$ in GtC/yr] is:

$$E_r(t) = \begin{cases} E_r(t-1) + \eta_r(t).E_r(t-1) & \text{if } w_r(t-1) > w^* \\ Eref_r(t) & \text{otherwise} \end{cases} \qquad (5.5)$$

where $Eref_r(t)$ represents the reference emissions of region r, and $E_r(t-1)$ is the emission allowance of region r of the previous time-step. The welfare trigger is the key parameter in this approach, whereas the three parameters, α, β and γ, are tuning variables used to reproduce the global emissions (sum of the regional emissions) that best fit the global emission profile. The variable γ determines the so-called grace period. In this period the regions should slow down their annual growth of emissions prior to the beginning of absolute reductions. The coefficients α and β influence the overall rate of emission reduction. Parameter α has a large impact on the emission allowances of regions with a per capita income slightly above the welfare trigger w^*, while parameter β strongly affects emission reduction rates when welfare is far from this threshold (Jacoby et al., 1999) (see also Figure 5.3).

When applying the Jacoby rule, the per capita welfare trigger is chosen as a percentage of the 1995 per capita welfare of the Annex I regions. After this key parameter is chosen, the three tuning parameters are set by trial and error. First, the initial grace period γ is selected, avoiding abrupt changes in regional emission allowances, followed by the tuning of the parameters α and β to reproduce the global emission profile as best as possible.

When all parameters are set, a scaling factor - calculated as the global emission profile minus the emission allowances for the regions not joining the burden-sharing - is introduced. This is divided by the emission allowances of all participating regions. The calculated emission allowances for the regions that join burden sharing are then multiplied by this scaling factor, reproducing the global emission profile.

An analysis of the Jacoby Rule approach is presented in den Elzen et al. (2003b).

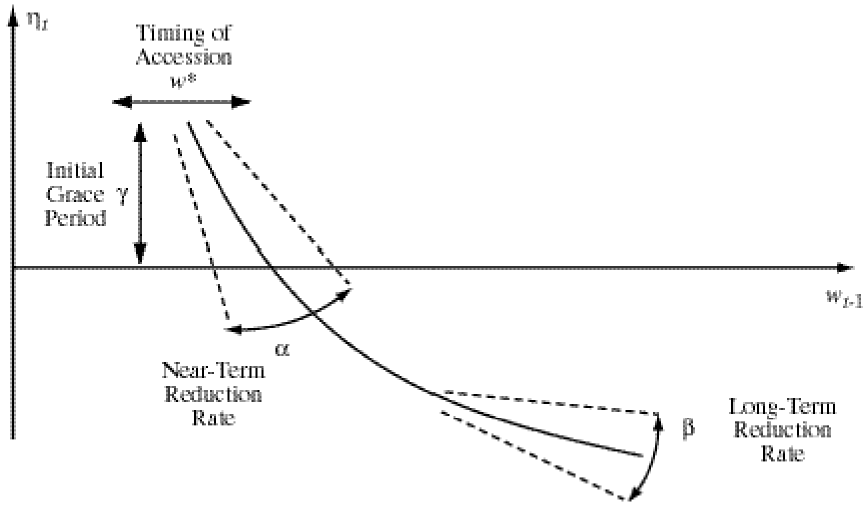

Figure 5.3. An example to illustrate the 'Jacoby rule' methodology (Jacoby et al., 1999).

Table 5.20. Main policy parameters of the Jacoby rule approach

- Participation threshold: income threshold in %-1990 Annex I per capita income in PPP$ or US$ per capita x year
- Differentiation of commitments based on per capita income (in PPP$)
- Tuning parameters α, β and γ
- Scaling to fit with emission profile (top-down approach) or no-scaling (bottom-up approach)

5.11 Triptych approach

The Triptych approach is a sector- and technology-oriented bottom-up approach allowing different national circumstances to be taken into account. The approach has been used for supporting decision-making on internal target differentiation in the European Union both before and after Kyoto (COP-3) (Blok et al., 1997; Phylipsen et al., 1998; Ringius, 1999). The Triptych approach is, in principle, bottom-up, but can also be combined with specific emission targets, as illustrated in den Elzen (2002; 1999). A global application of the Triptych approach was explored earlier in two studies: Groenenberg et al. (2001) and den Elzen et al. (1999). Groenenberg (2002) has updated the Triptych approach, which dealt with a number of shortcomings in both initial global applications.[39] For example, the growth in industrial production now accounts for structural economic sector changes. This update also uses approaches similar to the previous described approaches, and a multi-gas approach has been adopted where GWPs are used to convert all gases to CO_2-equivalent units, instead of calculations on the basis of (fossil) CO_2 emissions only. This updated approach also makes a specific attempt to incorporate some widely supported notions in the climate debate, especially the necessity of technological improvement, the transition to low greenhouse gas energy and the desirability of narrowing per capita emission differences.

The design of the regime aims at defining criteria and rules for differentiating future commitments for all regions in a consistent and transparent way. The Triptych approach, as implemented in the FAIR 2.0 model, is based on the updated Triptych of Groenenberg (2002) using the same methodology. The difference is that the population and economic

[39] Den Elzen (2002; 1999) presented an earlier version of this new Triptych approach, which uses the same methodology and assumptions, except that it was applied to (fossil) CO_2 emissions only.

growth scenarios are now based on the IPCC SRES scenarios included in the FAIR model, instead of the exogenous trajectories assumed in Groenenberg (2002).

Table 5.21. Main characteristics of the Triptych approach

- Focus on capability principle, but also egalitarian principle
- sector and technology-oriented approach
- Bottom-up approach
- Global participation
- Differentiated commitments

Methodology - Three categories or sectors of emission sources are distinguished in the Triptych approach:
1. the internationally-oriented energy-intensive industry sector;
2. the domestic sector;
3. the power-production sector.

The selection of the Triptych categories is based on two considerations: (i) different sectors in the national economies require different approaches to achieve a fair distribution of efforts, and (ii) national circumstances (standards of living, resources and economic structure) vary widely. The Triptych approach as described in Groenenberg (2002) also includes the GHG emissions of three others sectors, i.e. emissions from fossil fuel production, agriculture and deforestation.[40]

Different criteria are used for the different sectors to calculate partial emission allowances. More specifically, Groenenberg (2002) prescribes convergence trajectories in each of the three energy-consuming sectors: convergence of energy efficiency in the energy-intensive industrial sector, convergence of GHG emission intensity in electricity production and convergence of per capita emissions in the domestic sector. Global long-term targets are defined for each of these variables. Improvement and transfer of technology will be necessary for ultimate achievement of these targets. The total calculated emission allowances add up to binding national emission allowances.

1. The internationally oriented energy-intensive industry

a. *Description.* Internationally oriented energy-intensive industry covers internationally oriented industrial enterprises, where competitiveness is determined by the costs of energy and energy efficiency. In the Triptych approach the sector covers the following six subsectors: iron and steel, chemicals, pulp and paper, non-metallic minerals, non-ferrous metals and the energy transformation. The energy transformation sector includes petroleum refining, manufacture of solid fuels, coal mining, oil and gas extraction and any energy transformation other than power production. GHGs emitted from this sector compromise combustion-related emissions of CO_2, CH_4 and N_2O, as well as process emissions of N_2O (mainly from production of nitric and adipic acid) and PFCs (from the production of aluminium). Compared to other economic sectors, this industrial sector generally has a relatively high-energy use per value added and in most regions also high GHG per value-added ratio. Countries with a high share of heavy industry will therefore have relatively higher GHG emissions per unit of GDP than countries that focus primarily on light industry and services.

[40] In our default FAIR calculations, the deforestation emissions are excluded in the calculations of future commitments; calculations are based only on baseline emissions or other scenarios.

The international character of this sector implies that countries lacking sizeable energy-intensive industries themselves import goods from other countries and thus indirectly benefit from other countries' efforts in this sector. Apart from international specialisation, the share of heavy industry in the overall economy is generally related to a country's level of development. Initially, at a low level of development a country's share is low, but with increasing development its share tends to increase at the expense of primary sectors (agriculture, mining). Only at later stages of development does the share of energy-intensive industry in the total economy tend to decrease again with the growth in the share of the service sector. For these reasons, countries should not necessarily be penalised for relatively high emissions from this sector.

b. *Calculation of emission allowances.* The regional allowable GHG emissions are calculated on the basis of: (i) a realistic growth of production in the energy-intensive industry, (ii) a convergence of energy intensity (energy used per unit of production) and (iii) an achievable reduction in GHG emission intensity of the energy consumption (greenhouse gas emissions per unit of energy use).

(i) Growth of production. Projections of future physical growth in the energy-intensive industry are estimated on the basis of a detailed study of recent (mid-1980s to mid-1990s) historical trends in per capita physical production in various countries (Groenenberg et al., 2002). Growth rates are differentiated per country on the basis of five income groups. Based on these data, a continuous curve is composed to represent differentiated growth rates of per capita physical production in the energy-intensive industry as a function of per capita PPP income (in PPP-corrected 1995 US$ per capita). This is used here for the calculation of the future growth (see Figure 5.4). Growth rates of per capita production in the energy-intensive industry are high for the low-income regions. For the middle-income regions, the growth rates show a decreasing trend for future income when it is increasing. For the high-income regions, growth rates are already low, and these converge to even lower growth rates when income increases.

(ii) Energy intensity of production. For the energy-intensity levels a world-wide convergence in energy efficiency levels of all regions over time is assumed. A convenient indicator for energy efficiency is the Energy Efficiency Indicator (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 a reference SEC level. The reference SEC is equal to the SEC with best current practices or best available technologies. For example, an EEI of 105 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[41] by implementing the reference level technology. Here, the SEC of a package of energy-intensive commodities is used instead of a single product. This results in aggregated EEIs for all regions, each representing a relative measure of the average efficiency of the energy-intensive industry in that specific region (Groenenberg et al., 2002; Phylipsen, 2000).[42]

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[41] 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).

[42] These EEI_{act} are calculated as $En_{act}/ \Sigma_i\, m_i.SEC_{ref,i}$, where En_{act} is the energy consumption in the energy-intensive industry, m_I, the production quantity of subsector *i* (six subsectors) and $SEC_{ref,I}$, the reference SEC for subsector *i* (Phylipsen, 2000).

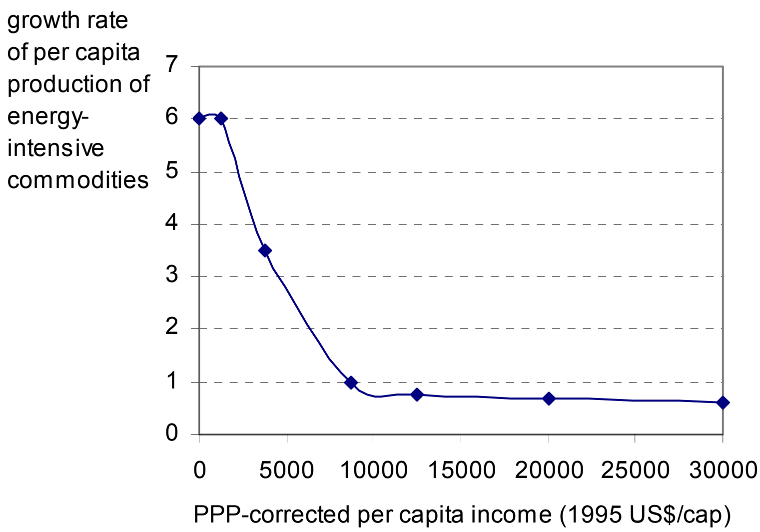


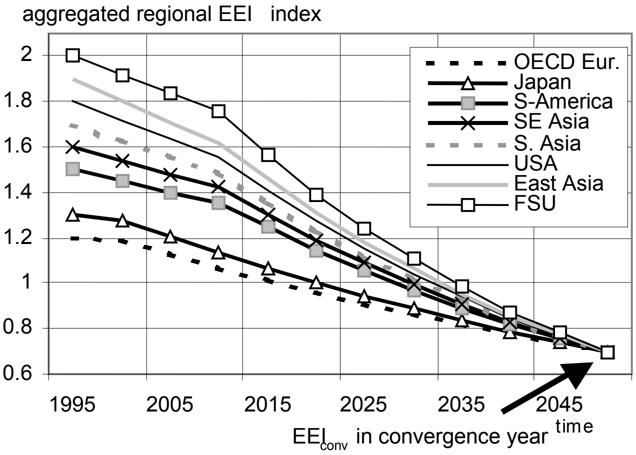
Figure 5.4. The overall annual growth rates of per capita commodity production for the energy- intensive industry as a function of the per capita income (1995 US$ PPP).

If aggregated EEIs for all regions converge at the same level, the required rate of energy efficiency improvement (*eff*) (in % per year) can be calculated from the regional actual EEI (EEI_{act}), convergence level of the EEI (EEI_{conv}) and convergence time period (tp_{conv}). In equation:

$$eff = 100.0 * \left[1.0 - (EEI_{conv} / EEI_{act})^{tp_{conv}}\right] \qquad (5.6)$$

(iii) Greenhouse gas intensity in energy use. This indicator represents two different dimensions of a change on the energy supply side: the shift in the relative use of different fossil fuel types (coal, oil, natural gas) and the change in the share of non-fossil fuels (nuclear, hydro-power, wind, solar, biomass). Here, a constant de-carbonisation rate (reduction in greenhouse gas intensity of the energy consumption) is assumed, which is the same for all regions.

For the default calculations we assume that the aggregated EEI index of all regions will ultimately converge at a level of 0.7 by the year 2050 (see Figure 5.5). Lower and upper values for the feasible EEI by 2050 were estimated to be 0.5 and 0.75, respectively. This final convergence level means that energy-intensive commodities will be produced at two-thirds of the current reference, specific, energy consumption levels (the energy consumption levels under best practices). Indications are that for a set of energy-intensive commodities energy requirements could, theoretically (i.e. down to thermodynamic minimal energy requirements), be lowered by almost two-thirds (Groenenberg, 2002). The yearly rates of energy efficiency improvements (in per cent per year) over the convergence period are calculated on the basis of equation 5.6, as summarised in the legend of Figure 5.5. After the convergence year, the EEI index improves with a certain percentage per year, which is equal for all regions. This global improvement rate is calculated on the basis of the final EEI level (for example, 0.5, the lower value in the EEI range) in a target year (for example 2100).



Regions	1995-EEI:	eff (%/yr)
OECD Europe	1.2	1.7
Japan	1.3	1.9
Canada	1.3	1.9
Latin America	1.5	2.5
South East Asia	1.6	2.6
Middle East	1.6	2.6
Africa	1.6	2.6
South Asia	1.7	2.7
Oceania	1.7	2.4
Eastern Europe	1.7	2.4
United States	1.8	2.8
East Asia	1.9	2.9
Former Soviet Union	2.0	3.1

Figure 5.5. The convergence in the aggregated Energy Efficiency Indices (EEIs) by 2050 (reference case) to half the current reference level. The legend shows the 1995 Aggregated Energy Efficiency Indices (EEIs) at regional level (Groenenberg et al., 2002)) and the calculated yearly energy efficiency improvements in per cent per year for the convergence period.

2. The domestic sector

a. *Description.* The domestic sector includes the residential sector (households), and commercial, transportation, light industry and agricultural sectors. The domestic sector also consists ofnon-CO_2 emissions, which is about 16% of the total emissions. CH_4 and N_2O emissions relate to both combustion in this sector and to waste, the latter including emissions from landfills and wastewater treatment. Emissions from the fluorinated gases are derived from a range of sources (semi-conductors, refrigeration, air conditioning equipment, fire extinguishers, aerosol applications).
b. *Calculation of emission allowances*. 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, at workplaces and those needing transport, etc. Therefore a per capita convergence approach is assumed to be appropriate here. No baseline growth assumptions are made for the domestic sectors. Instead, the regional domestic GHG emission allowance per capita converges to a convergence level of per capita domestic emission. For our default calculations, the base value of Groenenberg (2002) of 2.0 tCO_2-eq. per capita in 2050 is used, with a range of 1.5 to 3.0 tCO_2-eq. per capita. The convergence can be linear (linear pathway from 2010 per capita emissions towards convergence level), or non-linear, i.e. using a constant yearly rate of reductions or increase from 2020 per capita levels towards convergence levels. The final convergence level could also be a percentage of the present 1995 world average per capita domestic emissions. Furthermore, there is the option of just following the baseline domestic emissions.

   To enable us to compare the results of the Triptych approach to the other top-down approaches, the bottom-up approach for the domestic sector can also be adjusted to a top-down approach. In this case, the convergence in domestic per capita emissions by 2050 accommodates the emission space available for domestic emissions under the global domestic emission ceiling. This domestic emission ceiling is equal to the difference between the ceiling for global GHG emissions and the sum of the emissions allocated to the power and energy-intensive industry sector, as well as the GHG emissions from fossil fuel production and agriculture.

3. The power production sector

a. *Description of the sector.* The power production sector is treated separately because specific GHG emissions from power production vary to a large extent due to large differences in the share 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 fuel mix in power generation is an important national circumstance to take into account in the differentiation of commitments. In the analysis this sector includes both centralised and decentralised electricity production. In the emissions from power production the combustion related non-CO_2 emissions are also included, but these form only 1% of the total GHG emissions.

b. *Calculation of emission allowances.* The allowable GHG emissions from the power sector are defined by (i) a realistic growth in the electricity consumption and (ii) a convergence in the greenhouse gas intensity of energy consumption (GHG emissions per unit of energy consumption).

(i) Growth in energy consumption. The growth in the energy supply of the power sector can be assumed to be estimated by the weighted sum of the emission growth in the energy-intensive industry and the domestic sectors. Furthermore, the share of the two sectors in power consumption is assumed to remain constant in the future; this assumption is based on their present (1995) share in total final energy consumption (IEA, 1997a; IEA, 1997b). This rather simplistic assumption may need improvement.
(ii) Greenhouse gas intensity of energy consumption. A convergence of greenhouse gas intensities of the electricity produced to low greenhouse gas intensity levels is assumed for the change in the greenhouse gas intensity due to electricity production. Figure 5.6 shows this convergence towards the low value of 115 gCO_2/kWh in 2050 (den Elzen, 2002). This low intensity level is calculated on the basis of share of renewables and gas-based capacity, with a high conversion efficiency in total electricity production in the convergence year.

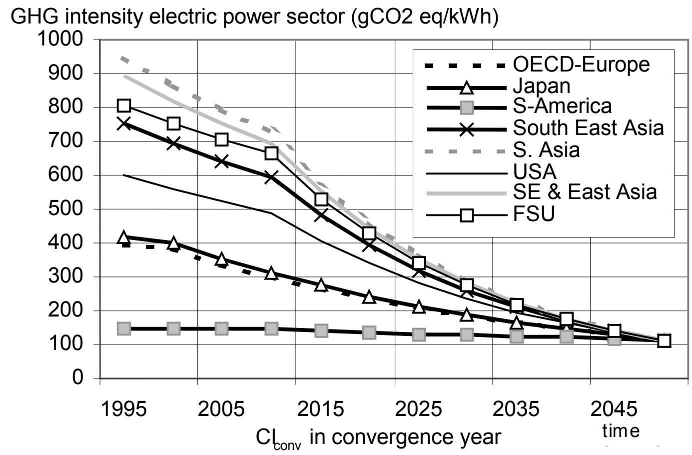


Figure 5.6. The convergence to the same level of greenhouse gas intensities due to electricity production (e.g. 115 gCO2 eq./kWh) (den Elzen, 2002). The legend shows the 1995 greenhouse gas intensities of electricity at the regional level (IEA, 1997a; IEA, 1997b).

For the default calculations the convergence level of the greenhouse gas intensity in the power sector (GHG emissions per unit of electricity production) is based on a 60% share of renewables in power generation in the convergence year, 2050 (as in projections by

Johansson (1993)). This is complemented with gas-based capacity with a high conversion efficiency (i.e. 70%), leading to a final greenhouse gas intensity level of 200 gCO_2/kWh in 2050, with a range of 125-300 gCO_2/kWh (Groenenberg, 2002). After the convergence year, the greenhouse gas intensity improves by a certain percentage per year, which is equal for all regions. This global improvement rate is calculated on the basis of the final level (for example, 125gCO_2/kWh as the lower value) in a target year e.g. 2100.

4. Fossil fuel production

Methane emission from coal mining, and from oil and gas production and distribution, amounts to only about 5% of the total (2000) GHG emissions; however, this can be reduced drastically up to 95% below the 1995 levels. Since large reductions are already achieved in the baseline emissions (efficiency improvements), we assume the emissions from this sector to be scaled with the ratio baseline emissions and triptych emissions from the three energy-consuming sectors. An additional reduction factor, default set at 1, further reduces the emissions.

5. Agriculture

For the CH_4 and N_2O agricultural emissions, for which no MACs are currently available, the emissions are assumed to be linearly reduced in the default calculations by 35%, compared to their baseline emissions between 2020 and 2040 for the S550e profile, and between 2025 and 2050 for the S650e profile.

Analyses of the Triptych approach are presented in den Elzen et al. (1999) and den Elzen (2002).

Table 5.22. Main policy parameters of the Triptych approach

1. Energy-intensive industry sector
- Growth rates of per capita production of energy-intensive commodities (see Figure 5.4)
- Year of convergence Energy Efficiency Index
- Level of convergence Energy Efficiency Index (see Figure 5.5)
- Global improvement rate after convergence year (calculated with target year and final target level)

2. Domestic sectors
- Year of convergence of per capita emissions
- Level of convergence of per capita domestic emission in (a) absolute level (in tCO_2 per capita x year), or (b) in %-world average per capita domestic emissions
- Type of convergence from 2010 to convergence level: (a) linear or (b) non-linear
- Other assumptions: (a) bottom-up (as described above), (b) following domestic baseline emissions or (c) top-down (domestic emissions calculated as GHG emission profile minus the emissions of all other sectors

3. Power production sector
- Year of convergence emission intensity
- Level of convergence emission intensity (in gCO_2/kWh)
- Global improvement rate after convergence year (calculated with target year and final target level)

4. Fossil fuel production
- Scaling factor of triptych emissions and baseline emissions
- Additional reduction factor

5. Agricultural emissions
- Reduction percentage compared to baseline emissions in a target year
- Starting year and target year for final reductions

6 Abatement costs and emission trading model

The FAIR 2.0 cost model was originally designed for the Dutch Ministry of Environment for the evaluation of the Kyoto Protocol under the Bonn and Marrakech agreements (den Elzen and de Moor (2001a; 2001b; 2002a; 2002b)). The original CO_2-only model has now been extended with non-CO_2 cost information and sinks, while new sets of CO_2 MAC curves are also included. Next to Kyoto analysis, the model can also be used to evaluate the economic impacts of future commitment regimes. It makes use of aggregated permit demand and supply curves, derived from Marginal Abatement Cost (MACs) curves for the different regions, gases and sources (Appendix A). These permit demand and supply curves are used to compute the international market equilibrium permit price (henceforth known simply as 'market price') under different regulation schemes on the basis of the same methodology as applied in Ellerman and Decaux (1998) and Criqui et al. (2001; 1999). This model can be used to: 1) distribute the emission reduction objective over the different regions, gases and sources following a least-cost approach; 2) calculate the market price and determine the buyers and sellers on the international trading market; and 3) calculate the regional mitigation costs and emission reductions after trading.

6.1 Marginal Abatement Cost (MAC) curves

Since abatement may be less expensive in some countries than in others, MAC curves differ according to the region. For instance, in a highly energy-inefficient economy, it takes less effort to reduce emissions. Given a certain emission reduction, the marginal costs can thus also differ. The MAC curves can thus be used as an indication of abatement costs per region, given a certain reduction target. The curves can also be used to model the effects of international emission trading by equalising the marginal costs of different regions, gases and sources through the construction of demand and supply curves (see Section 6.2).

The use of MAC curves in models such as FAIR has a number of advantages. These curves allow for the calculation of the costs and revenues of permit trading and can determine the sellers and buyers on the market. Furthermore, they clearly show the effects of permit trading and allow for a policy-relevant analysis of the permit market, including the implications of the behaviour and strategies of the various market players. The MAC curve methodology can also be used to point out the cheapest emission reduction options by spreading the emission reduction objective over the different sources following a least-cost approach. These elements provide the basis for conducting policy evaluations of, for instance, the Bonn-Marrakesh Agreement. However, simple models based on MAC curves also face a number of limitations. First of all, they cannot take carbon leakage[43] into account. Another disadvantage is that MAC curves only represent the direct cost effects but not the various linkages and rebound effects via the economy; i.e.: there is no direct link with macroeconomic indicators such as GDP losses or other measures of income of utility loss. MAC curves are also commonly taken as given, but in reality, MAC curves may shift

[43] Carbon leakage occurs as the effect of climate change policies in Annex I countries 'leaks away' through increasing emissions elsewhere. As energy in Annex I countries becomes more expensive, their energy-intensive industries may relocate to non-Annex I countries where there are no emission targets and energy is relatively cheaper (trade channel). Relatively low energy prices in these non-Annex I countries may cause production processes to become even more energy-intensive (price channel). On average, carbon leakage (the increase in emissions as a percentage of the reduction in Annex I) may run up to about 20%. As emission trading reduces compliance costs, the distortions on energy prices are much lower. Hence carbon leakage will be more than halved.

over time or may be dependent on the abatement efforts in other countries. Finally, emission reductions do not lead to structural changes, resulting in an unaffected baseline.

6.2 Aggregated demand & supply curves

In terms of emission trading, a MAC curve represents the willingness of a Party to import permits (i.e. demand), or to abate more than is required (i.e. supply). This willingness of a Party to buy or sell permits depends on the relation of the market price to its autarkic marginal price, i.e. the price for its emission reduction objective (Ellerman and Decaux, 1998). More specifically, if the market price is lower than its autarkic marginal price, it will be cheaper for this Party to buy permits up to the quantity difference between the autarkic emission reduction and the domestic abatement it would undertake at the market price. If the market price is higher than its autarkic marginal abatement cost, the Party would be willing to undertake more abatement up to the amount it would abate at the market price and supply the extra permits to the market.

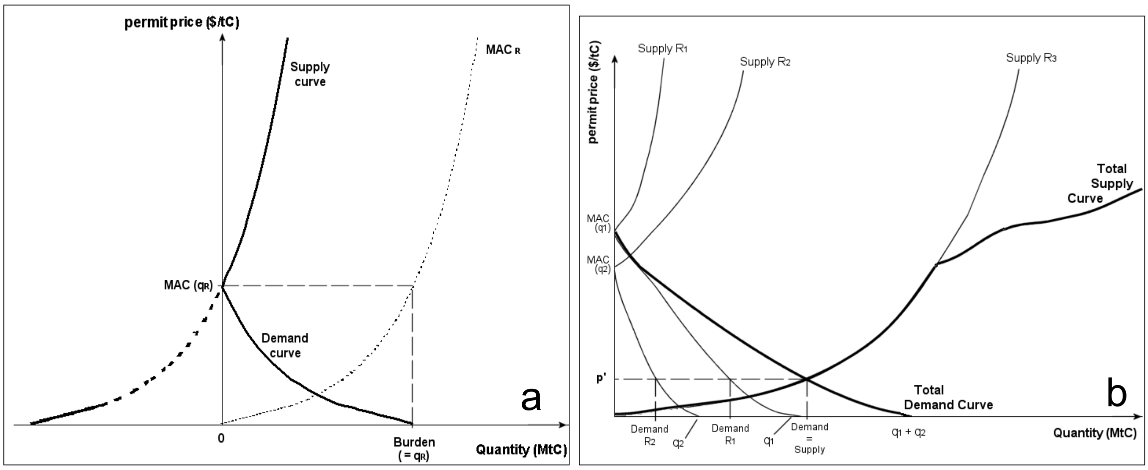


Figure 6.1. Construction of (a) the demand and supply and (b) the aggregated demand and supply curves.

In a perfect market, the market price is calculated using the following methodology (see also den Elzen and Both 2002):

1. Construct the supply curve for all participating regions by shifting the MAC over the horizontal axis to the left at a quantity corresponding to the burden (q_R) (Figure 6.1a).
2. Construct the demand curve for all participating regions by reversing the negative part of the supply curve (Figure 6.1b).
3. Construct the total demand and supply curve by simply adding up the quantities (x-axis) potentially supplied and those potentially demanded at each price (y-axis) across the constituent regions on the international market (Figure 6.1b).
4. Determine the international permit price (p') based on the intersection of the total demand with total supply curve. The projection on the x-axis represents the total quantity traded on a particular market (Figure 6.2b).

This methodology can be adapted to account for concrete caps on permit imports and exports (via import restrictions or a minimum market price), transaction costs associated with Kyoto Mechanisms, a CDM-accessibility factor reflecting the operational availability of viable CDM projects and the banking of excess emission allowances (see den Elzen and Both (2002)).

The transaction costs represent a combination of the total costs of emission exports (as percentage) and a fixed price for every tonne of carbon equivalents[44]. These costs are associated with the use of the Kyoto Mechanisms (KMs), i.e. International Emission Trading (IET), Joint Implementation (JI) and the Clean Development Mechanism (CDM). The CDM accessibility factor only applies to the unconstrained regions and can be set at a certain percentage in 2010, increasing linearly in time.

When the market price is known, it can be projected back on the regional MAC curves to determine the regional emission reductions, the total regional demand and supply can be constructed in combination with the regional emission reduction objectives. Finally, the demand and supply can be combined with the MAC curves and the market price to determine the total regional abatement costs.

Table 6.1. Main policy parameters for emission trading

- Selection of the CO_2 MAC curves (TIMER / POLES / WorldScan)
- Minimum internal reduction (%)
- Minimum market price ($/tCeq)
- Transaction costs as percentage of the marginal costs (%)
- Absolute transaction costs ($/tCeq)
- CDM accessibility factor (%)

6.3 Multi-gas demand & supply curves

Sectoral CO_2-equivalent demand- and supply-curves are used to allow for a multi-gas optimisation. However, the methodology described above needs some modifications. A demand and a supply curve, derived from the CO_2 and non-CO_2 sectoral MAC curves, is created for every emission source and every region (see Tables 3.6 and 3.7). These demand and a supply curves can all be aggregated over the regions and sources to create the total demand and supply curves. This result in the following consecutive steps:

1. Determining the regional autarkic marginal prices by projecting the regional reduction objectives on the regional aggregated MAC curves (Figure 6.2a).
2. Projecting the regional autarkic marginal prices on the regional sectoral MAC curves to determine the regional least-cost sectoral emission reduction objectives (Figure 6.2a).
3. Using the sectoral MAC curves combined with the regional least-cost sectoral emission reduction objectives to determine the sectoral demand and supply curves per region (Figure 6.2b).
4. Constructing the total demand and supply curves by simply adding up the quantities of the sectoral demand and supply curves for each price of all the regions (Figure 6.1b).
5. Determining the international market equilibrium permit price as the intersection of the total demand and supply curves. On the x-axis, this point represents the total quantity traded on the market (Figure 6.1b).

Again, the international market equilibrium permit price can be combined with the sectoral MAC curves per region to determine the total demand and supply per source, and per region, and to calculate the total regional abatement costs.

An extra policy parameter for multi-gas emission trading is the selection of the non-CO_2 MAC curves (GECS / EMF 21).

[44] This factor is new compared to the earlier function of the transaction costs used in den Elzen and Both (2002).

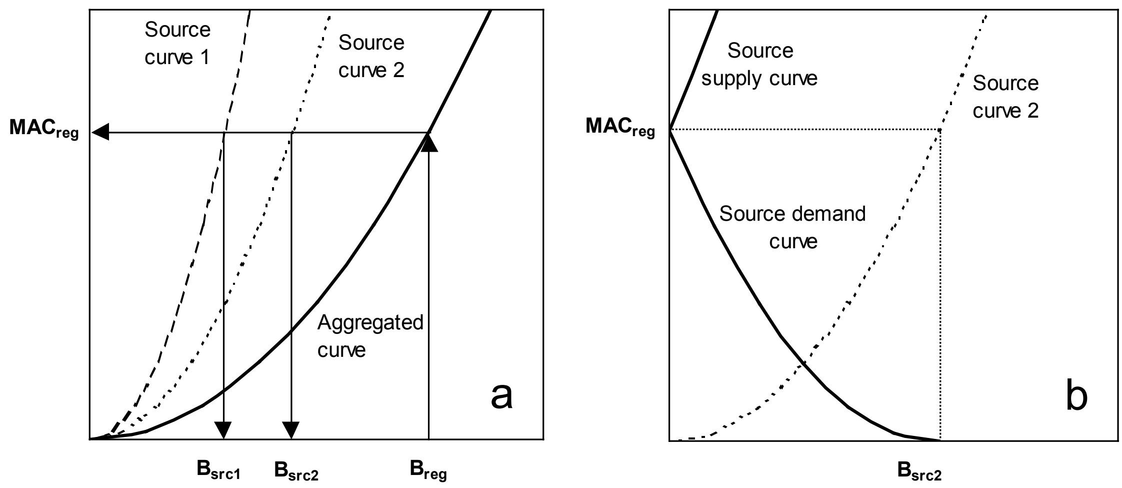


Figure 6.2. The creation of the sectoral demand and supply curves within a region. B_{reg} is the total regional burden, MAC_{reg} the accompanying marginal costs of that region and B_{src1} and B_{src2} the domestic sectoral burdens of sectors 1 and 2 in this region.

Box 6. Price caps

The above-described methodology calculates the regional costs resulting from a certain future commitment regime. Applying a least-cost approach results, for all climate regimes, in the same emission reductions per region when a perfect trading market is assumed with full participation of all world regions. In this case, the future commitment regime is transformed from a 'who reduces what into a who pays what' question. To control the regional costs, a 'safety valve' or 'price cap' can be introduced (Jacoby and Ellerman, 2002). The central idea is that the costs of the emission reduction objectives can be limited by buying permits from the regulatory authority at a pre-determined price. Therefore, when the permit price is greater than expected, the marginal price would be limited to the capped price.

The implementation of the price cap in the FAIR model is slightly different than the mechanism described above. A tax profile can be created to describe the world carbon tax development in time. Applying this carbon tax results in regional multi-gas emission reductions up to the carbon tax as marginal costs. The tax profile therefore results in regional emission profiles that can be analysed with the climate model for the resulting climate impacts. In this way the implemented price cap system gives an indication of the total emission reductions, accompanying climate impacts and the abatement costs when a certain world carbon tax is set. Because the implemented price cap approach does not start from a reduction objective but from a tax profile, no extra reduction credits are bought from the regulatory authority. Therefore the abatement costs only take the actual costs of emission reductions into account and not the extra costs for failing to reach the reduction objective.

6.4 Kyoto implementation

For the Kyoto implementation the assigned amounts for all Annex I regions participating in the Kyoto Protocol[45] are calculated by applying the Kyoto emission reduction objectives to the base-year CO_2-equivalent emission estimates.

[45] Default: all Annex I regions excuding the USA.

Base-year emissions - Because several specific articles of the KP lead to other country-specific base-years than 1990 (UNFCCC (1997b), we first have to calculate these base-year emissions (for more details see den Elzen and de Moor (2001b)). One provision stems from Article 3.5, which allows some economies in transition to use base-years other than 1990.[46] Related to Article 3.7 is the adjustment for Annex I Parties for whom land-use change and forestry constitutes a net source of greenhouse gas emissions in 1990. They are allowed to add their 1990 emissions from deforestation to their base-year emissions. Finally, Article 3.8 states that any Annex I Party may use 1995 as the base-year for some halocarbons, i.e. non-CO_2 gases such as hydrofluorcarbons, perfluorocarbons and sulphur hexafluoride. This is particularly relevant for Japan.

Table 6.2. Quantified emission limitation or reduction commitment (QUELRs) in percentage of base-year or 1990 emissions of all greenhouse gases for the Annex I regions

	Base-year emissions	1990 emissions	QUELR of KP (without sinks)		QUELR of Marrakesh (with sinks)	
Annex I regions	MtC/yr	MtC/yr	Base-year = 100	1990 = 100	Base-year = 100	1990 = 100
Canada	166.2	166.8	94.0	94.0	105.2	105.2
USA	1655.4	1649.7	93.0	93.3	96.3	96.6
West.Europe	1184.9	1177.2	92.2	92.5	93.8	94.2
East. Europe	374.5	326.7	92.9	106.6	95.0	108.9
Annex I FSU	1112.1	1114.7	99.8	99.7	103.9	103.9
Oceania	154.4	135.	106.8	122.1	114.5	130.6
Japan	334. 8	330.9	94.0	95.1	98.9	100.1
Total with USA	4982.3	4901.4	94.8	96.4	98.3	100.0
Total w/o USA	3326.9	3251.7	95.7	98.0	99.4	101.7

Sinks - Three articles of the Kyoto Protocol allow activities related to land use, land use change and forestry (LULUCF) to be counted as (domestic) sinks, i.e.: 1) Article 3.3 for afforestation, reforestation and deforestation (ARD); 2) Article 3.4 for forest management and 3) Article 3.4 for agricultural management (cropland & grazing land management), re-vegetation and conservation activities. The Bonn Agreement allows afforestation and reforestation projects to be eligible under CDM in non-Annex I countries, capped at a level of 1% of base-year emissions. The Bonn Agreement further limits the application of the sink potential in that only direct human-induced activities can be selected. Countries have to demonstrate that these activities have occurred since 1990 and are human-induced.[47] In the model, the sinks are taken as an exogenous assumption using FAO estimates and information in Appendix Z.[48] Because sinks credits are assumed to be far more cost-effective than credits from emission reductions, these credits are assumed to be negligible. Therefore we assumed the maximum allowance of emission reductions through sinks to be applied and used before other emission reductions are taken (for more details see den Elzen and de Moor (2001a)). The main decision in Marrakesh involved the additional 15 MtC of Russian sinks from forest management, i.e. the extra credits for sinks from forest management for Russia. In Bonn the cap amounted to nearly 18 MtC, but in Marrakech this was raised to 33 MtC. Table 6.2 presents the emission reduction compared to both the 1990 level and the base-year with and without the maximum amount of emission reduction

[46] This involves Bulgaria (1988), Hungary (average of 1985-1987); Poland (1988) and Romania (1989). Relative to 1990, this may effectively change the Kyoto targets for these countries; see UNFCCC (2000) and Appendix I.
[47] Indirect human-induced carbon removals through CO_2 and N fertilisation are excluded from the accounting framework.
[48] Carbon credits from forest management have been, if necessary, capped, except for Japan, Canada, Greece, Italy, Portugal, Slovenia, Spain, Switzerland, United Kingdom and the USA, where we used the reported values in Appendix Z (UNFCCC, 2001a).

through sinks, while Table 6.2 presents the regional calculations for sinks for the Annex I regions.

Table 6.3. Estimated achievable carbon credits from LULUCF activities under Articles 3.3 & 3.4, and CDM for the Bonn-Marrakesh Agreement

	Domestic sinks credits					CDM-sinks			
Annex I countries	Base-year emis-sions*	1.Carbon credits from ARD Art 3.3	2.Carbon credits from forest management (App. Z) Art 3.4	3. Carbon credits from agricultural management (no cap) Art 3.4	To-tal	4.Sinks - CDM projects for non-Annex I Art 12	Total carbon credits	%-Base year	Corrected assigned amounts
	MtC/yr	MtC/yr	MtC/yr	MtC/yr	MtC/yr	MtC/yr	MtC/yr	%	Base-year = 100
Canada	166	0.00	12.00	5.00	17.00	1.66	18.7	11.2%	105.2
US	1655	0.00	28.00	10.20	38.20	16.55	54.8	3.3%	96.3
Western Europe	1184	2.07	6.06	0.32	8.45	11.85	20.3	1.7%	93.7
Eastern Europe	375	0.00	3.75	0.00	3.75	3.74	7.5	2.0%	95.0
FSU	1112	0.00	34.83	0.00	34.83	11.12	46.0	3.9%	103.9
Oceania	154.	7.64	0.20	2.18	10.02	1.54	11.6	7.5%	114.5
Japan	335	0.00	13.00	0.00	13.00	3.35	16.4	4.9%	98.9
Annex I w. US	4982	9.7	97.9	17.7	125.3	49.8	175.0	3.2%	98.1
Annex I w/o US	3326	9.7	69.8	7.5	87.0	33.3	120.3	3.1%	98.9

* Base-year emissions are based on the Pronk proposal from COP 6 in The Hague (Pronk, 2001) Source: FAO data (TBFRA, 2000).

US withdrawal – For the USA, the implementation of the proposed GHG intensity target as described in the US Bush Climate Change Initiative in which -18% between 2002 and 2012) was adopted as the default (de Moor et al., 2002b; White-House, 2002a; White-House, 2002b).

Participation of Kazakhstan - The model also takes account of Kazakhstan's probable joining of the Kyoto Protocol. Because Kazakhstan is included in the FSU region, this region can be used with or without Kazakhstan.

Banking of surplus emission - Banking of surplus emission allowances is also allowed. The surplus emission allowances can be withdrawn from the market and saved for the second commitment period, thereby lowering the demand and raising the market price. In this way, the revenues of the regions supplying permits will be raised. Optimal banking is withdrawing a selective number of permits from the market, thereby maximising the region's revenues. An optimal banking strategy can result in revenue maximisation for the regions supplying joint surplus emissions.

Partial participation in emission trading - A final option is the participation of the different regions in emission trading on the emission trading market. This allows the user to assess the impact of the withdrawal of the USA and Australia from the Kyoto Protocol, or the impact of excluding particular non-Annex I regions from the emission trading market, thereby reducing the CDM projects. Most issues addressed in this section are extensively described in den Elzen and de Moor (2002b).

Table 6.4. Main policy parameters for the Kyoto calculations

- Base-year correction (yes / no)
- Sinks included as mitigation option to achieve the Kyoto targets period (no sinks / total sinks as agreed in the Bonn agreement / total sinks as agreed in the Marrakesh accords)
- Participation level of the Annex I regions in Kyoto Protocol
- Implementation of the Bush Climate Change Initiative (yes / no)
- FSU region (incl. Kazakhstan / excl. Kazakhstan)
- Banking of surplus emission allowances (%)
- Optimal banking (yes / no)
- Participation in the emissions trading market (Annex I and non-Annex I regions)

6.5 Costs calculations of post-Kyoto climate regimes

The cost model combines the regional emission reduction objectives, resulting from a regime of future commitments, as calculated with the emission allocation model of FAIR 2.0 (Chapter 5), with the MAC curves from the database to simulate an emission trading market. The model uses both CO_2 and non-CO_2 MAC curves combined with exogenous assumptions of forest management sinks and abatement potential for the non-CO_2 land-use emissions. As already explained in Chapter 3, the CO_2 MAC curves from TIMER and POLES include technological development, according to which the efficiency of processes improves with accumulated output (‘learning-by-doing’). Furthermore, both models set limitations on capital turnover, leading to inertia between the carbon tax and the resulting abatement effort. Both effects result in more realistic picture of cost estimates for future climate regimes, with amounts of costs included in the MAC curves.[49]

Technological progress - Contrary to the CO_2 MAC curves, the non-CO_2 curves are only available for the year 2010, thereby excluding technological improvements and inertia (frozen technology). Exogenous assumptions on technological improvements have been applied to make the non-CO_2 MAC curves more compatible with the CO_2 curves. These technological improvements encompass a yearly reduction potential improvement (see Figure 6.3a) expressed as a percentile improvement per five years.

Baseline correction - Although the different IPCC SRES emission scenarios do not include abatement effort related to climate policy, these baselines include scenario- dependent emission reductions due to efficiency improvements of power plants and industry or acidification policies, for example. However, because these abatement options are included in the non-CO_2 MAC curves, they have to be filtered out before cost calculations can take place. For every sectoral baseline, an estimate of the abatement action already taken in terms of reduction in the emission factors is calculated from the baseline emissions and the physical production/activity. Considering that we apply a least-cost optimisation, the most cost-effective emission reductions are assumed to have already been taken in the baselines and are therefore subtracted from the MAC curves (see Figure 6.3b).

Sinks in future commitments – The carbon credits from ARD sinks are calculated in the overall cost calculation using the MAC curve of ARD sinks. These credits are combined with

[49] With the present version of the FAIR model, it is not yet possible to assess their individual and combined effects. However, this can be done by producing MAC curves with the TIMER model with and without either effect.

estimates of sinks on forest management and estimates on the maximum abatement action for the non-CO_2 land-use emissions.[50] We have applied conservative estimates for forest management sinks. For the Annex I regions, credits are assumed to remain constant after Kyoto on the basis of the FAO (2000) and Appendix Z of the Marrakesh Accords. For the non-Annex I regions, we apply the lowest Annex I forest management credit per area unit, and multiply this with the forest area of the region. These estimates result in a total number of credits amounting to 141 MtCeq.[51]

Non-CO_2 land-use emission reductions -An exogenous estimate is made for the non-CO_2 land-use emissions for which no MAC curves are available on their abatement potential. For these sectors, we assume that emission reductions start taking place when the market price reaches a level of approximately 100 $/tCeq (default). The emission reduction is in this way dependent on the emission profile used, while the abatement effort increases in time to a maximum percentage of 35%.

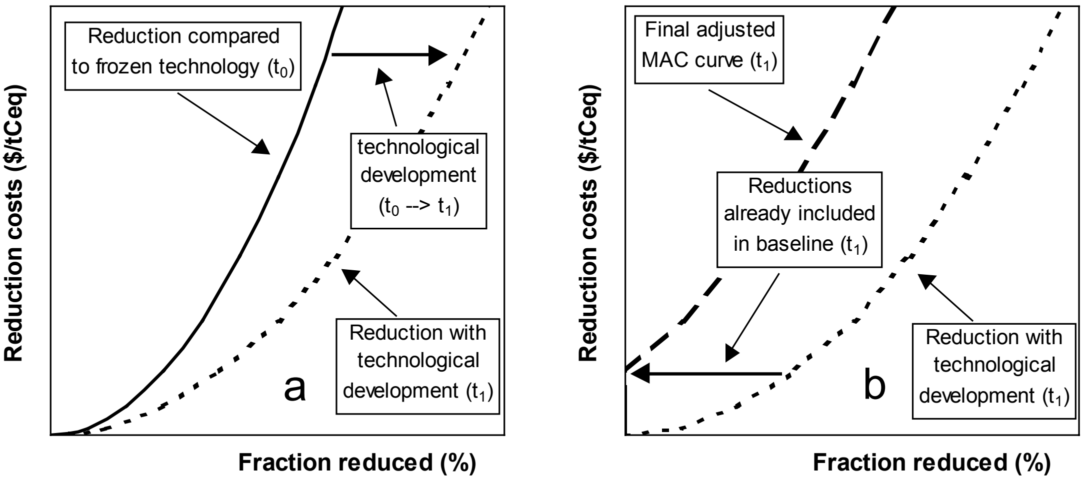


Figure 6.3. Technological development (a) and baseline correction (b) for the non-CO_2 MAC curves.

Table 6.5. Main policy parameters for the future commitments on costs calculations

- Technological progress (% per 5 years)
- Baseline correction (yes / no)
- Sinks in future commitments (MtCeq. / no)
- Starting year for the non-CO_2 land use emission reduction increase
- End year for the non-CO_2 land use emission reduction increase
- Maximum level of non-CO_2 land use emission reductions (%)

[50] The set of MAC curves does not include curves that describe the reduction potential and costs for non-CO_2 land-use emissions, while their emissions show an increase for almost all emission scenarios throughout the 21st century. If the carbon price also increases due to a higher emission reduction objective, it would seem implausible not to abate these emissions.

[51] Forest management credits for the Annex I regions: Canada: 12 MtC, USA: 28 MtC, OECD Europe: 6 MtC, Eastern Europe: 4 MtC, FSU: 35 MtC, Oceania: 7 MtC and Japan: 2 MtC. Non-Annex I regions: South America: 20 MtC, Northern Africa: 0 MtC, Western Africa: 8 MtC, Eastern Africa: 2 MtC, Southern Africa: 3 MtC, Middle East: 0 MtC, South Asia: 2 MtC, East Asia: 2 MtC, South East Asia: 6 MtC.

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Appendix A. The different sets of MAC curves

CO_2 MAC curves of WorldScan

Figure A.1 shows the MAC curves of the WorldScan model for the WorldScan implementation of the IPCC SRES A1B scenario[52] for the main regions in terms of relative emission reductions compared to the emission scenario levels, in order to show the variations across regions. Figure A.1 clearly shows that the MAC curves differ strongly between the various regions. For example, a carbon tax of US$30/tC[53] results in a 8-11% relative for the OECD Annex I regions (Canada, US, Western Europe, New Zealand, Australia and Japan), 16% for Eastern Europe, 25% for the Former Soviet Union (FSU), 30% for China and 35-40% for India and Africa. This pattern reflects that according to WorldScan the more cost-effective abatement options can be found in the non-Annex I regions (Africa, India and China) and the non-OECD90 Annex I regions (FSU and Eastern Europe). The MAC curves of the high emission scenarios (such as IPCC SRES A1b scenario) are lower than the MAC curves of the low emission scenarios (such as the IPCC SRES B1 and A2), although the differences are very small.

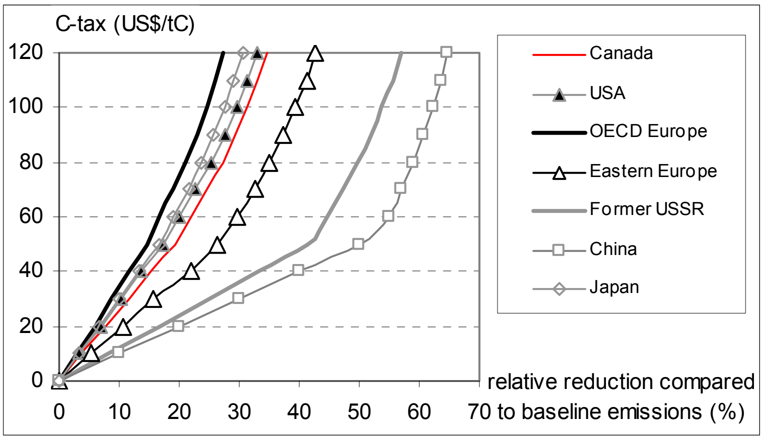

Figure A.1. The Marginal Abatement Cost (MAC) curves of WorldScan for the A1B scenario (used in the default calculations).

CO_2 MAC curves of TIMER

The MAC curves from TIMER can be created in two different ways, i.e.: using a block tax or using a linear tax. When a block tax is applied, the desired tax for a certain year is already applied in 2000, resulting in a horizontal tax level. When a linear tax is applied, the tax level increases linearly in time from 0$/tCeq in 2000 towards the desired tax in the year for which the cost curve is created. The MAC curves used in the model and presented in Figure A.2 are created by applying a linear tax from 0$/tCeq in 2000 until the desired tax in 2010 to calculate the MAC curve of 2010. Because the international permit price in 2010 is around 10 $/tCeq (Lucas et al., 2003), the MAC curves beyond 2010 are constructed by applying a linear tax from 10$/tCeq in 2010 towards the desired tax in the year for which the cost curve is created.

[52] This scenario reflects high economic growth with rapid introduction of new and more efficient technologies.
[53] The US$ in this study are: US$95.

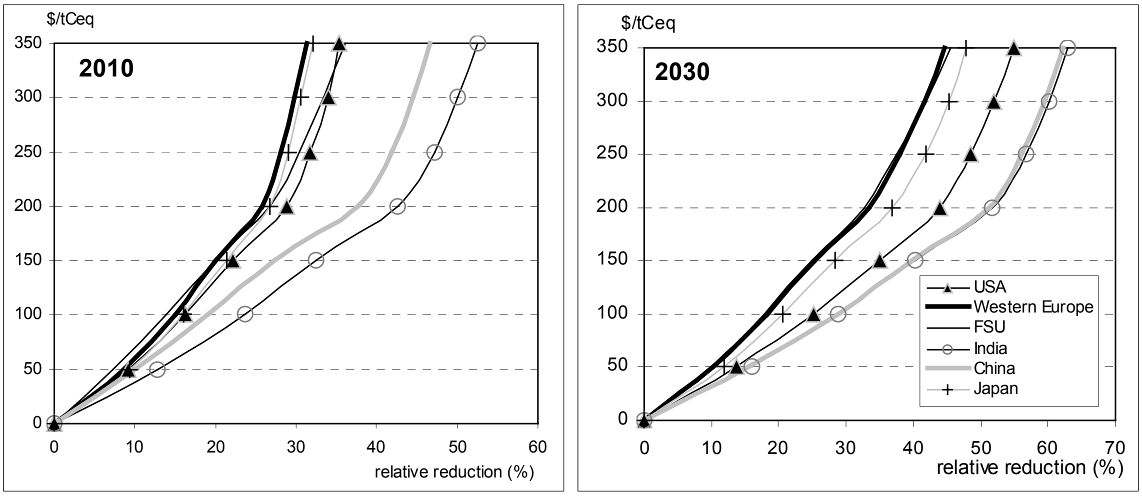

Figure A.2. The MAC curves of TIMER (2010 and 2030) for the A1B scenario.

Just as for WorldScan, also the TIMER MAC curves do not differ very much for the various scenarios. Figure A.2 shows the range in the marginal costs for the various regions. For example, for a carbon tax of US$150/tC, the relative reductions vary from approximately 20-30% in 2010 and 25-40% in 2030. The lower MAC curves are found for China and India, whereas the higher MAC are found for the OECD regions and for the FSU.

CO_2 MAC curves of POLES

The MAC curves in POLES are assessed by applying the same methodology used for the creation of the MAC curves of WorldScan and TIMER, as described in Section 3.5.3. The same inertia and technological learning as in TIMER are also modeled in POLES. The MAC curves are presented in Figure A.3. The MAC curves are somewhat lower than the MAC curves of TIMER for OECD Europe, USA, FSU and China, but higher for Eastern Europe and Japan. For example, for a carbon tax of US$30/tC in 2010 results in a 4-8% relative reduction for the OECD Annex I regions (Canada, US, Western Europe, New Zealand, Australia and Japan) and Eastern Europe, 10% for the Former Soviet Union (FSU), 15% for China and 5-8% for India and Africa. These reduction percentage are considerable lower compared to the WorldScan values.

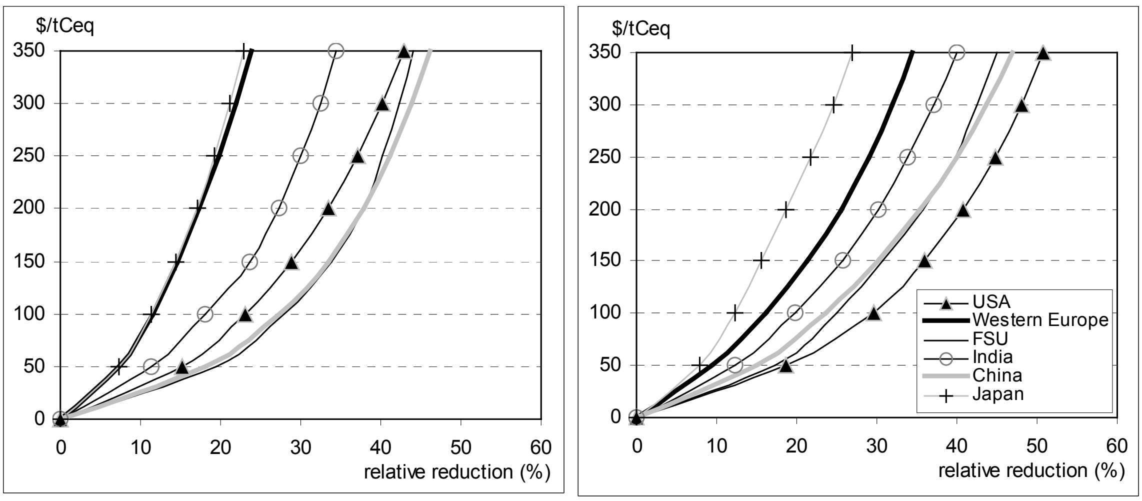

Figure A.3. The MAC curves of POLES (2010 and 2030) for the A1B scenario.

CO_2 sequestration MAC curves from IMAGE 2.2

Figure A.4 presents the MAC curves for sinks for the regions with the largest potentials in 2010 and 2030, based on the Common POLES-IMAGE (CPI) baseline. The FSU has the largest potential as well in 2010 as in 2030, while the potentials for all regions increase, partly due to a higher implementation factor and partly due to larger potentials because of more abandoned land. The OECD regions show larger costs per hectare, which is primarily caused by differences in the annual land costs per hectare.

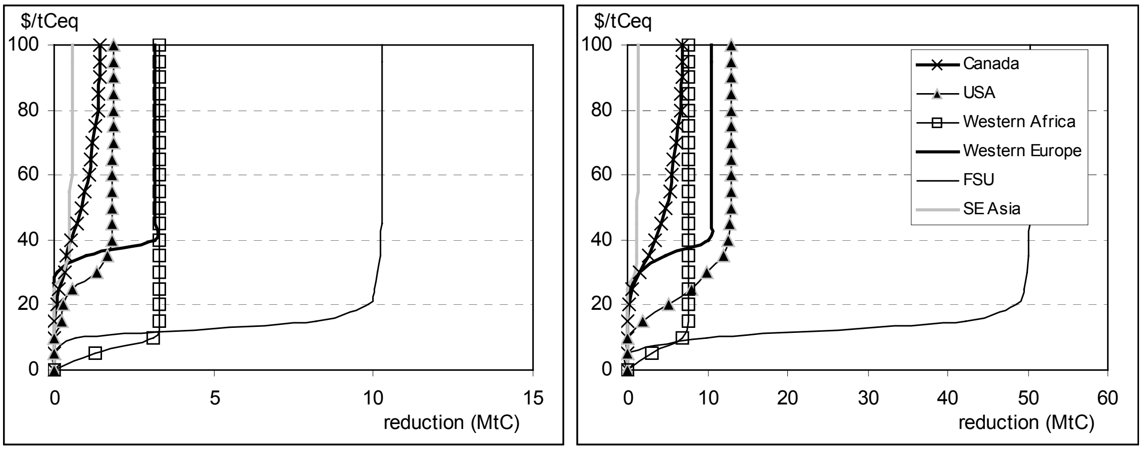

Figure A.4. The MAC curves of sinks from the IMAGE 2.2 model (2010 and 2030) for the A1B scenario.

Non-CO_2 MAC curves from the GECS project

Figure A.5 presents percentual MAC curves of the non-CO_2 GHGs for the different sources mentioned in Table 3.6 aggregated for the world. The figure clearly shows large differences in emission reduction potentials and overall abatement costs for the different sources. Abatement options in the CH_4 coal sector and for the PFCs are most cost-effective, while abatement for the N_2O transport sector is very expensive. Abatement in the CH_4 oil and waste sector are very cost-effective for reductions less than 30%, while abating more becomes very expensive. The same hold for abatements for SF_6, while abating more than 55% becomes very expensive.

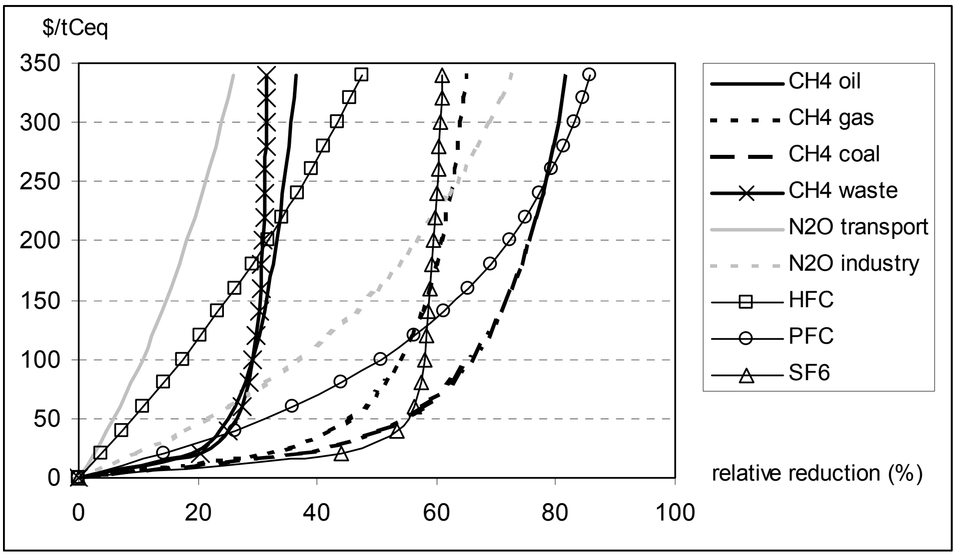

Figure A.5. The MAC curves of non-CO_2 of the GECS project

Non-CO_2 MAC curves of EMF 21

Figure A.6 presents the percentual MAC curves of EMF 21 for the different sources mentioned in Table 3.7 aggregated for the world. The figure clearly shows large differences in emission reduction potentials and overall abatement costs for the different sources. The most cost-effective abatements are in the N_2O industry and CH_4 coal sector with emission reduction potentials between 80% and 100%. On the contrary, abating emissions from manure management is very expensive and only has a potential of approximately 10%. The bottom up character of the curves is best seen for abatements in the CH_4 landfills sector, where new reduction options become cost-effective when the horizontal curve changes in a more vertical one.

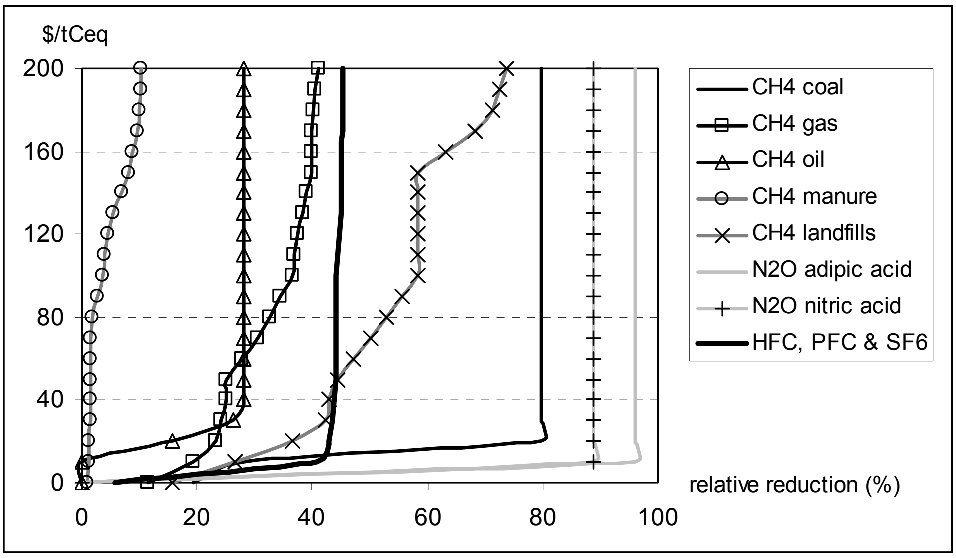

Figure A.6. The MAC curves of non-CO_2 of EMF 21

Appendix B. Model description of IMAGE-AOS, UNFCCC-ACCC and alternative climate models

This Appendix describes the equations and parameters used in IMAGE-AOS (‘IMAGE-AOS’) and the default configuration for UNFCCC-ACCC, and the alternative climate models.[54]

Emissions to Concentrations

Concentration (ρ , in ppmv) is defined as perturbation from a pre-industrial (‘background’) concentration (ρ_{pi}) caused by anthropogenic emissions. ρ is calculated from the integral of $\dot{\rho}$ (change of ρ in time)

$\rho(t) = \int_{t_0}^{t} \dot{\rho}(t')dt'$, with t_0 emission start date and t evaluation date. (B1)

The total global concentration including ‘background’ is defined as:

$\rho_{total}(t) = \rho(t) + \rho_{pi}$ (B2)

1) CO_2

$\rho_{pi} = 278$ ppmv.

$C_{CO_2} = 0.471$ ppmv/GtC (conversion factor for emissions to concentrations)

IMAGE-AOS

For global mean C-cycle calculations in IMAGE-AOS a mass conservation equation can be used, reflecting the global carbon balance:

$\dot{\rho}(t) = C_{CO_2}\left[E_{CO2}(t) - \left(S_{oc}(t) + E_{for}(t) + NEP(t)\right)\right]$ (B3c)

where $E_{CO_2}(t)$ is the total anthropogenic emissions, S_{oc} is the CO_2 uptake by the oceans, E_{for} the CO_2 uptake through forest regrowth and *NEP* is CO_2 uptake by the full-grown vegetation (all components in gigatons of carbon content per year = GtC/yr). In IMAGE-AOS, $E_{for}(t)$ and *NEP(t)* is exogenous input, taken from scenario runs of IMAGE 2.2. The latter calculates the terrestrial uptake from the atmosphere as altered by atmospheric CO_2 concentrations, climate change and different land cover conversions. The spatial resolution of the calculations is horizontally 0.5 degree latitude by 0.5 degree longitude. In addition, carbon storage and removal is calculated for 7 carbon pools (living biomass: leafs, stems, branches and roots, and dead biomass: litter, soil humus and charcoal) (Klein-Goldewijk et al., 1994; Alcamo et al., 1998; IMAGE-team, 2001). The oceanic uptake S_{oc} is calculated with the oceanic carbon model of IMAGE 2.2, i.e. the box-diffusion type oceanic carbon model of Joos et al. (1996; 1999). The model is based on a mixed-layer-pulse-response function, which allows for describing time-dependent non-linear effects of seawater chemistry resulting from changes in the atmospheric CO_2 concentration. The analytical representation (impulse response function, or known as a convolution integral) of the mixed layer response function of the Princeton 3-D model (Joos et al., 1996; 1999) is used. This model includes a positive temperature feedback on chemical CO_2 buffering system, leading to reduced transport to the deeper oceanic layers at higher temperatures.

UNFCCC-ACCC

$\dot{\rho}$ is defined as a summation of the time derivative of carbon content in *S+1* independent carbon pools:

$\dot{\rho}(t) = \sum_{s=0}^{S} \dot{\rho}_s(t)$, with $\dot{\rho}_0(t) = f_0 \cdot C_{CO_2} \cdot E_{CO_2}(t)$ and $\dot{\rho}_s(t) = f_s \cdot C_{CO_2} \cdot E_{CO_2}(t) - \rho_s(t)/\tau_s$ (B3a)

[54] This Appendix is based on Appendix C of den Elzen et al. (2002).

where $E_{CO_2}(t)$ the total anthropogenic emissions (emissions from fossil fuel combustion, industrial sources and land use changes) (GtC).
Combining equation (B1) and (B3a) gives the alternative expression of ρ by the convolution integral

$$\rho(t) = C_{CO_2} \int_{t_0}^{t} R(t-t') \cdot E(t')dt' \text{, with } R(t) = f_0 + \sum_{s=1}^{3} f_s e^{-t/\tau_s} \quad \text{(B3b)}$$

Table B.1. The coefficients f_s (-) and τ_s (years) as calculated by fiting the impulse response function with different Bern C-cycle models, as used in the UNFCCC-ACCC. The UNFCCC-ACCC default is Bern C-cycle of Joos et al. (1996; 1999), as used in the carbon cycle model calculations in the IPCC Second and Third Assessment Report (Bern SAR and TAR).

	Bern SAR (S=5)			Bern TAR (S=3)
coefficients	standard	low	high	standard
f_0	0.1369	0.1253	0.1504	0.152
f_1	0.1298	0.0909	0.1787	0.253
f_2	0.1938	0.1839	0.1798	0.279
f_3	0.2502	0.2674	0.2201	0.316
f_4	0.2086	0.2380	0.1725	
f_5	0.0807	0.0865	0.0975	
τ_1	371.6	407.2	330.8	171.0
τ_2	55.70	50.86	67.03	18.0
τ_3	17.01	15.19	21.72	2.57
τ_4	4.16	3.73	5.61	
τ_5	1.33	1.42	1.51	

2) non-CO_2

<u>IMAGE-AOS and UNFCCC-ACCC</u>

For both models, the change in concentration in time of non-CO_2 gas *g* (CH_4, N_2O, HFCs, PFCs, and SF_6) is defined by a single-lifetime expression:

$$\dot{\rho}_g(t) = C_g \cdot E_g(t) - \rho_g(t)/\tau_g \quad \text{(B4a)}$$

ρ_g and E_g are the concentration and emissions expressed in ppbv and $MtCH_4$ for CH_4, in ppbv and MtN for N_2O and in pptv and Mt for the other gases, and τ_g is the atmospheric lifetime.

Table B.2. Parameter values for different greenhouse gases used in equations (B2-B10), as used in the UNFCCC-ACCC model.

g	$\rho_{g,pi}$*		τ_g* (years)	C_g**		α_g* (10^{-3} Wm^{-2}/pptv)
CH_4	700	ppbv	8.4	0.353	ppbv/$MtCH_4$	
N_2O	270	ppbv	120	0.202	ppbv/MtN	
HFC-23	0	pptv	260	0.086	pptv/Mt	0.16
HFC-32	0	pptv	5	0.116	pptv/Mt	0.09
HFC-43-10mee	0	pptv	15	0.07442	pptv/Mt	0.40
HFC-125	0	pptv	29	0.05211	pptv/Mt	0.23
HFC-134a	0	pptv	13.8	0.07442	pptv/Mt	0.15
HFC-143a	0	pptv	52	0.07142	pptv/Mt	0.13
HFC-152a	0	pptv	1.4	0.09469	pptv/Mt	0.09
HFC-227ea	0	pptv	33	0.035	pptv/Mt	0.30
HFC-236fa	0	pptv	220	0.0394	pptv/Mt	0.28
HFC-245ca	0	pptv	5.9	0.0448	pptv/Mt	0.23
CF_4	44	pptv	50000	0.068	pptv/Mt	0.08
C_2F_6	0	pptv	10000	0.0508	pptv/Mt	0.26
SF_6	0	pptv	3200	0.041	pptv/Mt	0.52

* (Houghton et al., 2001), (Ramaswamy et al., 2001)
** (Alcamo, 1994)

<u>*IMAGE-AOS*</u>

For CH4, HCFCs and HFCs, fixed lifetimes are used in the UNFCCC-ACCC model. However, by default in IMAGE-AOS, lifetimes for these gases depend on OH abundance, because of the reactivity of these gases with the OH radical (Eickhout et al., 2002). τ_g for these gases is calculated based on the IPCC-TAR methodology (Prather et al., 2001) as follows:

$$\frac{1}{\tau_g(t)} = \frac{1}{\tau_{chemical}(t)} + \frac{1}{\tau_{stratospheric}} + \frac{1}{\tau_{soil-loss}} \qquad \text{(B5)}$$

where $\tau_{chemical}(t)$ is the time-dependant chemical lifetime, $\tau_{stratospheric}$ the lifetime due to loss to stratosphere and $\tau_{soil-loss}$ the lifetime due to loss to biosphere (only methane is absorbed by soils, with a specific time constant of 150 years (Harvey et al., 1997)). $\tau_{chemical}$ is determined by the reaction rate for the oxidation by OH radicals: $1/(\, k_{g+OH} \,.\, \rho[OH])$, with k_{g+OH} is the reaction rate (cm^3/years) and $\rho[OH]$ the OH concentration (molecules per cm^3). The OH concentration will depend on the emissions of CH_4 and the ozone precursors CO, NO_x and NMVOC, and determines the lifetimes of these compounds. In the IPCC-TAR, this dependency is represented by the linear interpolation mentioned in Table 4.11 in the TAR (Prather et al., 2001), with the use of sensitivity coefficients for the reaction of OH with CH_4, and the CO, NO_x and NMVOC. The chemical removal rate and atmospheric lifetime of methane also depend on the concentration of CH_4 itself. This important OH-feedback, the so-called chemical feedback is defined as $1/(1 + FF)$, in which the sensitivity FF represents the relative change (%) in the globally averaged CH_4 loss frequency for a +1% increase in CH_4 concentration above 1700 ppbv (1990-concentration) (Prather, 1994; Prather, 1996). The central IPCC-TAR value for *RR* is 1.45 (*FF*: -0.32%) (Prather et al., 2001). This means that tropospheric OH concentration declines by 0.32% for every 1% increase in CH_4. The change in concentration of the gases influenced by OH chemistry is now expressed by combining equation (B4a) and (B5):

$$\dot{\rho}_g(t) = C_g \cdot E_g(t) - \rho_g(t) / \tau_g(t) \qquad \text{(B4b)}$$

Concentrations to Radiative Forcing

<u>*IMAGE-AOS and UNFCCC-ACCC*</u>

In both models global radiative forcing $F_{total}(t)$ (Wm^{-2}) is calculated as the linear sum of forcing $F_g(t)$ (Wm^{-2}) by all gases g plus a contribution by aerosol forcing. The contribution to global radiative forcing by each greenhouse gas g is calculated using the following functional dependencies (Ramaswamy et al., 2001):

$$F_{CO_2}(t) = 5.325 \log(\rho_{total}(t) / \rho_{pi}) \qquad \text{(B6)}$$

$$F_{CH_4}(t) = 0.036 \left[\sqrt{\rho_{CH_4,total}(t)} - \sqrt{\rho_{CH_4,pi}} \right] - f\left(\rho_{CH_4,total}(t), \rho_{N_2O,pi}\right) + f\left(\rho_{CH_4,pi}, \rho_{N_2O,pi}\right) \qquad \text{(B7)}$$

$$F_{N_2O}(t) = 0.12 \left[\sqrt{\rho_{N_2O,total}(t)} - \sqrt{\rho_{N_2O,pi}} \right] - f\left(\rho_{CH_4,pi}, \rho_{N_2O,total}(t)\right) + f\left(\rho_{CH_4,pi}, \rho_{N_2O,pi}\right) \qquad \text{(B8)}$$

with the overlap forcing of CH_4 and N_2O defined by

$$f(\rho_{CH_4}, \rho_{N_2O}) = 0.47 \ln\left[1 + 2.01 \cdot 10^{-5} \left(\rho_{CH_4} \rho_{N_2O}\right)^{0.75} + 5.31 \cdot 10^{-15} \rho_{CH_4} \left(\rho_{CH_4} \rho_{N_2O}\right)^{1.72}\right] \qquad \text{(B9)}$$

For the other gases radiative forcing is given by

$$F_g(t) = \alpha_g \left(\rho_{g,total}(t) - \rho_{g,pi}\right) = \alpha_g \rho_g(t) \qquad \text{(B10)}$$

See Table B.2 for values of α_g .

The forcings of aerosols and of chlorinated and brominated halocarbons are used in the calculation of global radiative forcing, and thus global mean temperature increase, but not in the attribution of responsibility calculations.

<u>*IMAGE-AOS*</u>

The radiative forcing of tropospheric and stratospheric ozone and stratospheric water vapour is based on IPCC-TAR and Harvey (Harvey et al., 1997). The direct and indirect forcing from sulphate aerosols are calculated according to (Harvey et al., 1997). Hence, the direct effect is scaled linearly with the emissions of SO_2 and the indirect effect varies with the logarithm of SO_2 emissions.

The forcing of the fossil and biomss burning organic and black-carbon aerosol is based on the forcing functions, as described in (Eickhout et al., (2002).

UNFCCC-ACCC

A time series for total forcing by sulphate aerosols (direct + indirect) from the HadCM3 GCM is taken for both the historical period. After 1990, data is taken from the appropriate HadCM3 IPCC SRES scenario experiment.

Temparature Change and Sea Level Rise

IRFs

Both global mean surface-air temperature (*T*) and sea-level rise (*SLR*) are calculated by impulse response functions of radiative forcing, mathematically equivalent to a model consisting of two independent (parallel) box models:

$$\dot{T}(t) = \sum_{s=1}^{2} \dot{T}_s(t) = \sum_{s=1}^{2} \left[\frac{T_{eq}}{F_{eq}} \frac{a_s^T}{\tau_s^T} F_{total}(t) - T_s(t) / \tau_s^T \right] \quad \text{(B11)}$$

$$T(t) = \int_{t_0}^{t} \dot{T}(t')dt' \text{, which, with (B11), is equivalent to } T(t) = \frac{T_{eq}}{F_{eq}} \int_{t_0}^{t} R^T(t-t')F_{total}(t)dt' \quad \text{(B12)}$$

$$\text{with } R^T(t) = \sum_{s=1}^{2} \frac{a_s^T}{\tau_s^T} e^{-t/\tau_s^T} \quad \text{(B13)}$$

$$S\dot{L}R(t) = \sum_{s=1}^{2} S\dot{L}R_s(t) = \sum_{s=1}^{2} \left[\frac{SLR_{eq}}{F_{eq}} \frac{a_s^{SLR}}{\tau_s^{SLR}} F_{total}(t) - SLR_s(t) / \tau_s^{SLR} \right] \quad \text{(B14)}$$

$$SLR(t) = \int_{t_0}^{t} S\dot{L}R(t')dt' \text{, which, with (B14), is equivalent to } SLR(t) = \frac{SLR_{eq}}{F_{eq}} \int_{t_0}^{t} R^{SLR}(t-t')F_{total}(t)dt' \quad \text{(B15)}$$

$$\text{with } R^{SLR}(t) = \sum_{s=1}^{2} \frac{a_s^{SLR}}{\tau_s^{SLR}} e^{-t/\tau_s^{SLR}} \quad \text{(B16)}$$

IMAGE-AOS

IMAGE-AOS includes the Upwelling-Diffusion Climate Model (UDCM) of IMAGE 2.2 (Eickhout et al., 2002), which is used to derive global-mean surface-air temperature changes and temperature changes in the ocean from radiative forcings. UDCM is based on the MAGICC-model of Climate Research Unit (CRU) (Wigley and Schlesinger, 1985; Hulme et al., 2000; Raper et al., 2001). The model consists of an atmosphere box, two land and two ocean boxes (representing the Northern and Southern Hemisphere). The two ocean boxes are divided into 40 layers each, with a mixed layer on top that absorbs the energy of solar radiation. It is assumed that no energy is adsorbed above land. The energy balance of the climate system can be described as follows: $F = \lambda T + F_{oc}$, where F_{oc} is the net global-mean heat flux into the ocean. The term λT is the change in the rate of heat loss to space from the climate system. The feedback parameter λ is the inverse of the climate sensitivity. Hence, the radiative forcing is partitioned between increased heat loss to space and additional uptake of heat by the climate system (Raper et al., 2001). The absorbed heat is exchanged between the four boxes (determined by k_{LO} and k_{NS}; the land-ocean and northern-southern hemisphere exchange coefficient respectively). On time scales relevant to climate change, the atmosphere may be assumed to be in equilibrium with the underlying oceanic mixed layer. The absorbed heat is transported within each ocean box by diffusion and upwelling. The upwelling decreases at increasing temperatures of the ocean to simulate the slowing down of the thermohaline circulation of the ocean (Raper et al., 2001).

Sea level rise calculations are based calculations in UDCM. Thermal expansion is a non-linear function of the temperature in each oceanic layer (determined by UDCM). The influence by small glaciers is determined by the global mean surface temperature change, a minimum temperature at which the glacier would eventually disappear, an initial ice volume, the equilibrium ice volume and the glacier response time (Wigley and Raper, 1995). To take regional variations into account, a set of minimum temperatures and response times is applied. The influence by the Greenland and

Antarctica ice sheets is calculated with two factors (Wigley and Raper, 1993): one that represents the gain or loss of ice due to the initial state of the ice sheet (in 1880) plus a factor to describe the influence of temperature change on the ice sheets. The West Antarctic Ice Sheet contains enough ice to raise the sea level by 6 metres and has attracted special attention because it may result in rapid ice discharge due to weak surrounding ice shelves. However, it was concluded that this was very unlikely to happen in the 21st century (IPCC, 2001).

UNFCCC-ACCC

The default parameters for using equation (B11)-(B16) in UNFCCC-ACCC are given in Table B.3.

Table B.3. Parameter values for temperature calculations (left-column) and for sea level rise (right column) calculations and the in UNFCCC-ACCC. These parameters were taken from a fit to a HadCM3 experiment, with F_{eq} = 7.0 Wm^{-2}.

	SLR
T_{eq} = 7.3583 K	SLR_{eq} = 4.7395 m
τ_1^T = 8.4007 years	τ_1^{SLR} = 1700.2 years
a_1^T = 0.59557	a_1^{SLR} = 0.96677
τ_2^T = 409.54 years	τ_2^{SLR} = 33.788 years
a_2^T = 0.40443	a_2^{SLR} = 0.03323

Appendix C. Calculation of contributions of emission regions[55]

Concentrations

Calculations of concentration changes resulting from emissions are performed according to the equations in Appendix A for each emitting region seperately. For example, the change in CO_2 concentration for ACCC for region r is expressed as in equation (B3a):

$$\dot{\rho}^r(t) = \sum_{s=0}^{3} \dot{\rho}_s^r(t) \tag{C1}$$

with $\dot{\rho}_0^r(t) = f_0 \cdot C_{CO_2} \cdot E_{CO_2}^r(t)$ *and*

$$\dot{\rho}_s^r(t) = f_s \cdot C_{CO_2} \cdot E_{CO_2}^r(t) - \rho_s^r(t) / \tau_s \tag{C2a}$$

with $E_{CO_2}^r(t)$ the time series of anthropogenic emissions (PgC) for region *r*.

The total global CO_2 concentration is then calculated for a total of *R* regions as

$$\rho^{total}(t) = \sum_{r=1}^{R} \sum_{s=0}^{S} \rho_s^r(t) + \rho_{pi} = \sum_{r=1}^{R} \sum_{s=0}^{S} \int_{t_0}^{t} \dot{\rho}_s^r(t')dt' + \rho_{pi} \tag{C3}$$

which equals $\rho(t)$ as calculated using eqs. (B2) and (B3b)

Thus, in this approach, the global carbon cycle is divided into R hypothetical independent pools, one for each emitting region, described with the same C-cycle model and parameters. Concentrations and removal rates for region r therefore only depend on emissions of this one region, not on emissions of other regions. In fact there is only one global carbon cycle, of course, which further shows distinct non-linearities. The following alternative calculation of regional attribution of CO_2 concentrations appreciates this. A time-dependent single effective global mean turnover time $\tau(t)$ is defined by the global carbon balance:

$$\dot{\rho}(t) = C_{CO_2} E_{CO_2}(t) - \rho(t) / \tau(t) \tag{C4}$$

$\tau(t)$ can thus be calculated from global total emission and concentration (perurbations from pre-industrial):

$$\tau(t) = \frac{\rho(t)}{C_{CO_2} E_{CO_2}(t) - \dot{\rho}(t)} = \frac{\rho^{total}(t) - \rho_{pi}}{C_{CO_2} E_{CO_2}(t) - \dot{\rho}(t)} \tag{C5}$$

The single turnover time $\tau(t)$ is applied to each region at each time step, so that residence time of carbon in the 'region pools' is equal for all regions at each point in time*:*

$$\dot{\rho}^r(t) = C_{CO_2} \cdot E_{CO_2}^r(t) - \rho^r(t) / \tau(t) \text{, so that} \tag{C2b}$$

$$\dot{\rho}(t) = \sum_{r=1}^{R} \dot{\rho}^r(t) = \sum_{r=1}^{R} C_{CO_2} \cdot E_{CO_2}^r(t) - \sum_{r=1}^{R} \rho^r(t) \Big/ \tau(t) = C_{CO_2} \cdot E_{CO_2}(t) - \rho(t) / \tau(t)$$

Removal rate in each 'region pool' thus depends on global carbon-cycle dynamics, including non-linearities and emissions by all other regions. An advantage of this method is that global concentrations can be calculated from emissions using any C-cycle model, like the model described by equation (B3c). Attribution calculations are not restricted to a linearized model like the impulse response functions in equation (B3b).

The formulation (B2b), applying a single time-varying global turnover time to each emission region, is equivalent to splitting the change in global concentrations into an increase (emission) term and a decrease (removal) term:

$$\dot{\rho}(t) = \dot{\rho}_+(t) - \dot{\rho}_-(t) \Rightarrow \dot{\rho}_-(t) = \dot{\rho}_+(t) - \dot{\rho}\ \ (t) = C_{CO2} E\ \ (t) - \dot{\rho}(t) \tag{C6}$$

The global removal term is then applied to each region scaled by the contribution of that region to global concentrations:

[55] This Appendix is based on Appendix D of den Elzen et al. (2002).

$$\dot{\rho}_{-}^{r}(t)=\frac{\rho^{r}(t)}{\rho(t)}\dot{\rho}_{-}(t) \tag{C7}$$

The total change in concentrations for region *r* is then (using (C6) and (C7)):

$$\dot{\rho}^{r}(t)=\dot{\rho}_{+}^{r}(t)-\dot{\rho}_{-}^{r}(t)=C_{CO_2}E^{r}(t)-\frac{\rho^{r}(t)}{\rho(t)}\dot{\rho}_{-}(t)=C_{CO_2}E^{r}(t)-\frac{\rho^{r}(t)}{\rho(t)}\left(C_{CO2}E(t)-\dot{\rho}(t)\right)=$$

$$=C_{CO_2}E^{r}(t)-\rho^{r}\,\frac{C_{CO2}E(t)-\dot{\rho}(t)}{\rho(t)}=C_{CO_2}E^{r}(t)-\rho^{r}(t)/\tau(t)$$

Forcing

In the default case, non-linearities in radiative forcing are not accounted for. The contribution of region r to total global forcing is calculated as:

$$F^{r}(t)=\sum_{g=1}^{G}F_{g}^{total}(t)\frac{\rho_{g}^{r}(t)}{\rho_{g}(t)} \tag{C8a}$$

The summation is performed over all G greenhouse gases.

For the case of non-linearities, most importantly resulting from the saturation effect in CO_2 forcing, Enting (1998) proposed the following solution:

$$\dot{F}_{g}^{r}(t)=\frac{\partial F_{g}}{\partial\rho_{g}}\dot{\rho}_{g}^{r}\Rightarrow F^{r}(t)=\sum_{g=1}^{G}\int_{t_0}^{t}\frac{\partial F_{g}}{\partial\rho_{g}}(t')\cdot\dot{\rho}_{g}^{r}(t')dt' \tag{C8b}$$

Temperature Change and Sea Level Rise

As for concentrations, the same equations as applied globally in Appendix B are applied for each region individually, with global forcing replaced by attributed forcing from equation (C8a) or (C8b). For example, (B11) will become:

$$\dot{T}^{r}(t)=\sum_{s=1}^{2}\dot{T}_{s}^{r}(t)=\sum_{s=1}^{2}\left[\frac{T_{eq}}{F_{eq}}\frac{a_{s}^{T}}{\tau_{s}^{T}}F^{r}(t)-T_{s}^{r}(t)/\tau_{s}^{T}\right] \tag{B9}$$

and the convolution integral in (B12):

$$T^{r}(t)=\frac{T_{eq}}{F_{eq}}\int_{t_0}^{t}R^{T}(t-t')F^{r}(t)dt' \tag{B10}$$

Appendix D. Enhancing policy realism in the Multi-Stage approach: Policy delay, reference period

(i) *Policy delay*: In original MS analyses so far, countries immediately changed stage when trespassing any of the thresholds. In reality, (reliable) information about the threshold indicators is only available after some time (normally at 3-5 year). In addition, negotiations are needed to define commitments for countries that have met the threshold level. In the present Kyoto Protocol system, targets for future commitment periods ideally would be defined 5 years before the commitment period (CP) begins (in order to avoid interference with policy implementation). This would imply another five years of delay. However, it needs to be seen if this will be realised in practice. To account for the policy delay all MS approaches assume that if the threshold is achieved at the middle of the CP T (2010, 2015, …), then the country enters a new stage (stage 2 or stage 3) at T+1 (2015, 2020, …). This implies a policy delay of at least five years. A delay of 5 year can be considered the shortest delay thinkable; in practise a ten-year period would seem more likely.

(ii) *Reference period for threshold levels*: Using a single reference year for measuring whether a (non-Annex I) country has met a threshold level has a number of disadvantages. First, indicator values, like per capita emissions of income tend to fluctuate substantially from year to year. Second, such figures are generally surrounded by substantial uncertainty. Third, single reference year brings the risk of anticipative behaviour and/or fraud. These problems are reduced when the measurement of the threshold indicator is based on more robust multi-year averages. A suitable length of the reference period would seem between 5 - 10 years. However, in the perfect model world it is not necessary to introduce such a period, and we simply define for the reference year the value at commitment period T.

The implications of the reference period and policy delay factor in the model can be llustrated by the following example for the Multi-Stage 1 and Multi-Stage 2 cases: If a country's 2012 level meets the first threshold level, it will be noticed at time 2015, middle of the second CP (2013-2017). The country will adopt it first new emissions intensity target for 2020, the middle of third CP (2018-2022). To account for policy delays in the Multi-Stage 3 case, the end of the transition period is extended with a policy delay, necessary to fit with middle of the next CP.

Appendix E. Summary QUELRs of Annex I Parties

Table E.1 Quantified emission limitation or reduction commitment, in per cent of base year or 1990 emissions of all greenhouse gases (CO_2 equivalent)

	Base-year	1990 emis-sions	Assigned Amounts Kyoto '97	Sinks credits (Marra -kesh)	Assigned Amounts including sinks	QUELR Compared to base KP	QUELR Compared to base Marrakesh	QUELR Compared to1990 KP	QUELR Compared to1990 Marrakesh
Annex I Parties	MtC/yr	MtC/yr	MtC/yr	MtC/yr	MtC/yr	Base year = 100	Base year = 100	1990 = 100	1990 = 100
Australia	134.54	115.4	145.30	3.53	148.8	108	110.6	125.9	128.9
Austria	21.04	20.6	19.36	0.84	20.2	92	96.0	94.1	98.2
Belgium	37.24	37.2	34.37	0.40	34.8	92	93.1	92.4	93.4
Bulgaria	42.84	37.6	39.42	0.79	40.2	92	93.9	105.0	107.1
Canada	166.17	166.8	156.84	18.66	175.5	94	105.2	94.0	105.2
Czech Rep.	51.74	51.8	47.63	0.84	48.5	92	93.6	92.0	93.6
Denmark	19.08	19.0	17.55	0.33	17.9	92	93.7	92.5	94.2
Estonia	11.10	11.1	10.22	0.21	10.4	92	93.9	92.0	93.9
Finland	20.51	20.5	18.87	0.37	19.2	92	93.8	92.0	93.8
France	148.96	151.0	138.95	2.37	141.3	92	93.6	92.0	93.6
Germany	330.28	329.7	303.85	4.54	308.4	92	93.4	92.2	93.5
Greece	29.28	28.7	26.94	0.38	27.3	92	93.3	93.8	95.1
Hungary	27.72	23.6	26.05	0.57	26.6	94	96.0	110.3	112.7
Iceland	0.70	0.7	0.77	0.07	0.8	110	119.5	110.0	119.5
Ireland	14.59	14.6	13.42	1.10	14.5	92	99.6	92.0	99.6
Italy	141.64	141.4	130.36	2.07	132.4	92	93.5	92.2	93.6
Japan	334.78	330.9	314.71	16.35	331.1	94	98.9	95.1	100.1
Latvia	9.73	9.7	8.95	0.44	9.4	92	96.5	92.0	96.5
Liechtenstein	0.07	0.1	0.07	0.00	0.1	92	93.0	91.9	92.9
Lithuania	14.06	14.1	12.93	0.42	13.4	92	95.0	92.0	95.0
Luxembourg	3.67	3.7	3.37	0.05	3.4	92	93.3	92.0	93.3
Monaco	0.03	0.0	0.03	0.00	0.0	92	93.0	92.8	93.8
Netherlands	59.77	59.4	54.99	0.63	55.6	92	93.1	92.5	93.6
New Zealand	19.90	19.9	19.93	8.04	28.0	100	140.3	100.0	140.3
Norway	14.22	14.2	14.36	0.56	14.9	101	105.0	101.0	105.0
Poland	153.89	125.2	144.66	2.36	147.0	94	95.5	115.5	117.4
Portugal	17.12	17.4	16.02	0.39	16.4	92	94.2	92.0	94.2
Romania	72.24	62.5	66.46	1.82	68.3	92	94.5	106.4	109.3
Russia	826.56	829.1	829.11	41.3[56]	870.4	100	105.0	100.0	105.0
Slovakia	20.79	20.8	19.15	0.71	19.9	92	95.4	92.0	95.4
Slovenia	5.24	5.2	4.82	0.41	5.2	92	99.9	92.0	99.9
Spain	84.13	83.4	77.40	1.51	78.9	92	93.8	92.8	94.6
Sweden	19.25	18.9	17.71	0.77	18.5	92	96.0	93.6	97.7
Switzerland	14.46	14.5	13.30	0.65	14.0	92	96.5	92.0	96.5
Ukraine	250.70	250.7	250.70	3.62	254.3	100	101.4	100.0	101.4
UK	208.84	202.2	186.81	3.27	190.1	92	93.6	92.4	94.0
USA	1655.4	1649.7	1539.5	54.75	1594.3	93	96.3	93.3	96.6
Total with US	4982.3	4901.4	4724.9	175.0	4900.0	94.8	98.3	96.4	100.0
Total w/o US	3326.9	3251.7	3185.4	120.0	3306	95.7	99.4	98.0	101.7
Annex I regions									
Canada	166.17	166.8	156.8	18.66	175.5	94.0	105.2	94.0	105.2
USA	1655.4	1649.7	1539.5	54.75	1594.3	93.0	96.3	93.3	96.6
West.Europe	1184.9	1177.2	1088.5	20.30	1108.8	92.2	93.8	92.5	94.2
East. Europe	374.46	326.7	348.2	7.50	355.7	92.9	95.0	106.6	108.9
Annex I FSU	1112.1	1114.7	1111.9	46.00	1157.9	99.8	103.9	99.7	103.9
Oceania	154.4	135.	165.2	11.56	176.8	106.8	114.5	122.1	130.6
Japan	334.78	330.9	314.7	16.35	331.1	94.0	98.9	95.1	100.1
Annex I	4982.3	4901.4	4724.9	175.0	4900.0	94.8	98.3	96.4	100.0

[56] At the time of the Bonn Agreement this value was 25.9 MtC/yr (den Elzen and de Moor, 2001)

Appendix F. Detailed sinks estimates

Table FI.1 Estimates of emissions by sources and removals by sinks under Article 3.3 and 3.4 based on FAO data, accounting for the LULUCF caps as agreed in Bonn

	Base-year	Art 3.3 credit (+) or debit (-)	Art 3.4[57] Forest management	Art 3.3 debit compensated	Forest management after discount	Appendix Z	Art 3.4 Forest management 58	Art 3.4 Agricultural management (net-net)	Art 3.3 credits	Total Art 3.3 + 3.4	CDM 1% Base-year	Total credits	%-base-year
	1	2	3	4	5=0.15*((3)-(4))	6	7=min (6,5)	8	9	10=7+8+9	11	12=11+10	15
	MtC/yr	MtC/yr	MtC/yr	MtC/yr	MtC/yr	MtC/yr	MtC/yr	MtC/yr	MtC/yr	MtC/yr	MtC/yr		%
Australia	134.54	0.00	40.49	0.00	6.07	0.00	0.00	2.18		2.18	1.35	3.53	2.4%
Austria	21.04	-0.20	5.14	0.20	0.74	0.63	0.63			0.63	0.21	0.84	4.3%
Belgium	37.24		0.22		0.03	0.03	0.03			0.03	0.37	0.40	1.2%
Bulgaria	42.84		2.44		0.37	0.37	0.37			0.37	0.43	0.79	2.0%
Canada	166.17	-4.30	49	4.30	6.71	12.00	12.00	5.00		17.00	1.66	18.66	11.9%
Czech Republ.	51.74		2.13		0.32	0.32	0.32			0.32	0.52	0.84	1.8%
Denmark	19.08	0.09	0.31	0.00	0.05	0.05	0.05		0.09	0.14	0.19	0.33	1.9%
Estonia	11.10		0.64		0.10	0.10	0.10			0.10	0.11	0.21	2.0%
Finland	20.51	-0.36	5.65	0.36	0.79	0.16	0.16			0.16	0.21	0.37	1.9%
France	148.96	-0.62	8.95	0.62	1.25	0.88	0.88			0.88	1.49	2.37	1.7%
Germany	330.28	-0.21	14.07	0.21	2.08	1.24	1.24			1.24	3.30	4.54	1.5%
Greece	29.28		0.23		0.03	0.09	0.09			0.09	0.29	0.38	1.4%
Hungary	27.72		1.92		0.29	0.29	0.29			0.29	0.28	0.57	2.2%
Iceland	0.70	0.02	0	0.00	0.00	0.00	0.00	0.04	0.02	0.06	0.01	0.07	8.7%
Ireland	14.59	0.91	0.32	0.00	0.05	0.05	0.05		0.91	0.96	0.15	1.10	8.2%
Italy	141.64	0.47	0.71	0.00	0.11	0.18	0.18		0.47	0.65	1.42	2.07	1.6%
Japan	334.78	-1.02	13.58	1.02	1.88	13.00	13.00			13.00	3.35	16.35	5.2%
Latvia	9.73		2.52		0.38	0.34	0.34			0.34	0.10	0.44	4.9%
Liechtenstein	0.07				0.00	0.01	0.00			0.00	0.00	0.00	1.1%
Lithuania	14.06		1.88		0.28	0.28	0.28			0.28	0.14	0.42	3.3%
Luxembourg	3.67		0.01		0.00	0.01	0.01			0.01	0.04	0.05	1.4%
Monaco	0.03				0.00	0.00	0.00			0.00	0.00	0.00	1.1%
Netherlands	59.77	0.00	0.4	0.00	0.06	0.01	0.01	0.02	0.00	0.03	0.60	0.63	1.1%
New Zealand	19.90	7.64	3.67	0.00	0.55	0.20	0.20		7.64	7.84	0.20	8.04	40.4%
Norway	14.22	0.02	3.53	0.00	0.53	0.40	0.40		0.02	0.42	0.14	0.56	3.9%
Poland	153.89		5.45		0.82	0.82	0.82			0.82	1.54	2.36	1.6%
Portugal	17.12		0.51		0.08	0.22	0.22			0.22	0.17	0.39	2.5%
Romania	72.24		7.35		1.10	1.10	1.10			1.10	0.72	1.82	2.7%
Russian Federation[59]	826.56		425.5		63.83	33	33			33	8.27	25.90	3.1%
Slovakia	20.79		3.36		0.50	0.50	0.50			0.50	0.21	0.71	3.7%
Slovenia	5.24		1.78		0.27	0.36	0.36			0.36	0.05	0.41	8.6%
Spain	84.13		3		0.45	0.67	0.67			0.67	0.84	1.51	2.0%
Sweden	19.25	-0.09	10.89	0.09	1.62	0.58	0.58			0.58	0.19	0.77	4.4%
Switzerland	14.46	-0.02	0.66	0.02	0.10	0.50	0.50	0.01		0.51	0.14	0.65	4.9%
Ukraine	250.70		7.41	0.00	1.11	1.11	1.11			1.11	2.51	3.62	1.4%
UK	208.84	0.56	1.67	0.00	0.25	0.37	0.37	0.25	0.56	1.18	2.09	3.27	1.7%
USA	1655.38	-7.20	101.2	7.20	14.10	28.00	28.00	10.20		38.20	16.55	54.75	3.6%
TOTAL with USA	4982.25	-4.31	726.6	14.02	106.89	82.50	82.47	17.70	9.71	109.9	49.82	159.7	3.4%
Non-EU	3826.9	-4.86	674.5	12.5	99.3	77.3	77.3	17.4	7.7	102.4	38.3	140.7	3.8%
EU	1155.39	0.55	52.08	1.48	7.59	5.17	5.16	0.27	2.03	7.46	11.55	19.02	1.8%
TOTAL wo USA	3326.9	2.89	625.4	6.8	92.8		54.5	7.50	9.71	71.68	33.27	105.0	3.3%
FAIR Annex I regions													
Canada	166.17	-4.30	49.00	4.30	6.71	12.00	12.00	5.00	0.00	17.00	1.66	18.66	11.9%
USA	1655.38	-7.20	101.2	7.20	14.10	28.00	28.00	10.20	0.00	38.20	16.55	54.75	3.6%
West.Europe	1184.88	0.57	56.27	1.50	8.22	6.08	6.06	0.32	2.07	8.45	11.85	20.30	1.9%
East. Europe	374.46	0.00	24.43	0.00	3.66	3.76	3.75	0.00	0.00	3.75	3.74	7.50	2.2%
FSU	1112.14	0.00	438.9	0.00	65.70	19.46	19.46	0.00	0.00	19.46	11.12	30.58	2.8%
Oceania	154.44	7.64	44.16	0.00	6.62	0.20	0.20	2.18	7.64	10.02	1.54	11.56	7.0%
Japan	334.78	-1.02	13.58	1.02	1.88	13.00	13.00	0.00	0.00	13.00	3.35	16.35	5.2%
Annex I	4982.25	-4.31	726.6	14.02	106.89	82.50	82.47	17.70	9.71	109.9	49.8	159.7	3.4%

[57] Here we use the FAO data (TBFRA, 2000), as reported in Table 2 of Pronk (2001). Although Pronk is referring to Annex 3.B3 page 169, the numbers in Table 2 do not correspond with the reported FAO-data in Annex 3.B3. In particular, for Canada, Italy, Russia and US, these are higher. Since we already use the Appendix Z values for these regions, the final carbon credits from forest management do not change by using the updated FAO data.

[58] For Japan, Canada, Greece, Italy, Portugal, Slovenia, Spain, Switzerland, United Kingdom and the US, the values as given in Appendix Z are used.

[59] The amount of presented sinks credits in column 6, 7 and 10 include the extra credits for forest management granted at COP 7 in Marrakesh instead of the 17.63 MtC granted during COP 6 bis in Bonn.

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