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Abstract

To reinforce the long-term commitment to climate change mitigation, the post-2012 climate policy framework is aimed to be completed by 2009. The new agreement needs to include a wider participation of parties, and therefore needs to address the effort sharing of countries. The mitigation capabilities and the responsibilities of countries do however vary significantly. This can, in principle, be overcome with a cap-and-trade system, with which the question of equity is addressed trough the allocation of emission allowances.

A number of effort sharing schemes have been proposed. Effort sharing however suffers from a fundamental trade-off between detail and transparency on how the emission allocations are calculated. This study addresses this problem by comparing and combining the results from a transparent but simplified effort sharing model EVOC, and a detailed and – due to its complexity – seemingly non-transparent ETSAP-TIAM energy system model. The aim of the study is to evaluate the goodness of the initial effort sharing, particularly in terms of mitigation costs experienced by different regions in the scenarios.

Based on the long-term energy-climate scenarios crafted with the TIAM model, we assess the resulting consequences in emission profiles and the energy system, concentrating especially on regional mitigation costs and emission trading. Two cases of market failures in emission trading are also considered. Finally we compare the mitigation potentials between the two models and estimate the effect of EVOC recalibration on the national emission allowances. The results of the study underline particularly the importance of detailed and reliable assumptions for the mitigation potentials of different countries in the effort sharing process.

Preface

In 2006, VTT Technical Research Centre of Finland, the Government Institute for Economic Research (VATT) and Ecofys GmbH published a study that systematically tested the sensitivity of the Triptych method for Finland (Soimakallio et al. 2006) for the Finnish Ministry of the Environment. The study also analysed the suitability of the Triptych method for sharing emission allowances in general and provided certain improvement proposals based on critical factors for Finland.

This project, carried out by VTT and Ecofys, is based on the key conclusions of the above-mentioned project and study. The differences with regard to emission reduction possibilities between EVOC, a relatively simplified but transparent effort sharing tool, and ETSAP-TIAM, a more sophisticated but complex energy system model, are compared in this study. The results provide useful information for international climate negotiations.

The project was funded by the Finnish Environmental Cluster Research Programme, the Ministry of Employment and the Economy, and VTT Technical Research Centre of Finland. Ecofys worked with VTT as a subcontractor in this project.

The project's management group was leaded by Hanne Siikavirta (the Finnish Ministry of the Environment). The other members of the management group were Pekka Harju-Autti on behalf of the programme (the Finnish Ministry of the Environment), Erja Fagerlund (the Ministry of Employment and the Economy), Magnus Cederlöf (the Finnish Ministry of the Environment), Ilkka Savolainen (VTT) and Sanna Syri (VTT), with Sampo Soimakallio (VTT) as project leader and secretary of the management group.

The publication was written by Research Scientist Tommi Ekholm (VTT), Senior Research Scientist Sampo Soimakallio (VTT), Consultant Sara Moltmann (Ecofys GmbH), Manager Niklas Höhne (Ecofys GmbH) and Technology Manager Sanna Syri (VTT). The authors are grateful to the funders for making this project possible and the management group for directing the research work and providing useful comments on this publication.

Summary

Climate change poses a serious threat for the future and requires rapid and large-scale measures all over the world. The negotiations on the post-2012 climate policy framework began in 2005 and are aimed to be completed by 2009. The new policy framework needs to include more countries committed to deeper emission cuts in the future.

The capability and responsibility of countries to respond to emission reductions vary significantly, in particular between developing and developed countries. Consequently, differentiation of commitments to reduce emissions needs to take place. A cap-and-trade system can, at least in theory, separate the issues of efficiency and equity in mitigation efforts, turning the question of equity between countries to a question of how the initial allocation of emission rights should be made. A number of suggestions and viewpoints have been presented on global emission reductions and effort sharing the reduction requirements. However, the fundamental problem with effort sharing is the trade-off between the ability to consider national circumstances and a straightforward and transparent procedure to define the emission allocation.

In our study, two relatively sophisticated methods to share emission allowances, Triptych and Multistage, calculated by the simplified but transparent effort sharing tool EVOC, are analysed in long-term mitigation scenarios produced with a more sophisticated but complex global integrated assessment model of the TIMES family (ETSAP-TIAM). The scenarios incorporated two emission limits with concentration targets of 450 ppm CO_2-eq and 550 ppm CO_2-eq, and four economic and population growth projections. The aim of the study is to evaluate the goodness of the initial effort sharing, particularly in terms of mitigation costs experienced by different regions in the scenarios.

The cost-optimal mitigation strategy from of the TIMES model showed that most of the emission reductions would come from the energy sector and industry due to phasing out of fossil fuels. Other sectors would find it hard to reduce emissions to levels as low as in electricity generation, even though large mitigation potential still exists. With the stringent 450 ppm target, large involvement from all economic sectors – including agriculture – is needed, resulting in considerably higher allowance prices in 2050.

Globally, the mitigation costs exhibited a direct relationship with the assumed pace of economic growth as more expensive mitigation efforts have to be carried out with higher economic growth and thus energy demand. The costs were between 0.01% and 0.07% of global GDP with the 550 ppm target and 0.05% and 0.13% with the 450 ppm target in 2020 and, respectively, between 1% – 2.2% and 4% – 5.3% in 2050. The relatively low costs in 2020 and a steep rise thereafter result from the emission targets gradually tightening to stringent levels of –50% from 1990 levels by 2050.

The regional mitigation costs, measured as the change in energy system costs from the baseline to the reduction scenario, were often more influenced by emission trading, welfare losses and in some regions also by energy trade than actual investment or operation costs. Therefore, the costs were very different from the global overall cost in many regions, mostly above average in Annex I regions and below average or negative in most non-Annex I regions. As the trade costs and revenues result from trade flows and prices, trade costs are a second order result and thus more uncertain and prone to errors.

Based on the TIMES results, an effort sharing scheme that would equalize the mitigation costs of different regions was considered. The resulting effort sharing scheme allocated more emissions for the Middle East, Canada, Australia, the USA and Western Europe when compared to Triptych, less for developing Asia and Mexico, and relatively similar amounts for other regions.

The study also considered some imperfections in the emission markets, namely transaction costs and strategic behaviour by a country that is a large net seller. Both cases showed the importance of efficient allowance markets as both market imperfections resulted in roughly a doubling of global mitigation costs in 2020.

Emission reductions in different sectors vary relatively significantly between the cost-optimal solution calculated by TIMES and the Triptych approach calculated by EVOC. The sensitivity of the Triptych approach towards different sectoral targets was studied by recalibration of EVOC using the sectoral targets provided by TIMES. For certain regions, the overall emission reduction target changed significantly due to recalibration, illustrating the sensitivity of sectoral emission reductions assumed in the Triptych approach.

Although it is almost impossible to predict the actual effort levels of different countries, the study underlines the importance of detailed and reliable assumptions for the mitigation potentials of different countries. With the Triptych and Multistage approaches used, most developing countries would financially benefit from the cap-and-trade system. However, market imperfections might distort the efficiency of the system to a large extent, and in such cases the separability of equity and efficiency might not hold.

Contents

1. Introduction

The ultimate objective of the United Nations' Framework Convention on Climate Change (UNFCCC), agreed in Rio de Janeiro in 1992, is the stabilisation of atmospheric concentrations of greenhouse gases at a level that prevents dangerous anthropogenic interference with the climate system. The Kyoto Protocol under the UNFCCC, which came into force on 16 February 2005, is the first step towards reaching this objective. Under the Kyoto Protocol, the so-called Annex I countries have binding emission commitments for the period 2008–2012 to limit or reduce their greenhouse gas emissions by 5% from the level of 1990. Far more significant emission reductions and wider participation is required to reach the ultimate objective of the UNFCCC.

The official negotiations of post-2012 climate policy framework began in the Conference of the Parties (COP 11) held in Montreal in 2005. COP 13 held in Bali in 2007 culminated in the adoption of the Bali Road Map, which consists of a number of forward-looking decisions that represent the various tracks that are essential for reaching a secure climate future. The Bali Road Map includes the Bali Action Plan, which charts the course for a new negotiating process designed to tackle climate change, with the aim of completing this by 2009 (UNFCCC 2008).

A number of suggestions and viewpoints have been presented on global emission reductions and on sharing the effort in reducing the emissions. The term "effort sharing" in the context of mitigation of climate change typically indicates how greenhouse gas emission reduction commitments are differentiated between countries in a cap-and-trade system. The principal factor involved in the effort-sharing can be described as fairness or equity, which has different types of scope. There are various perspectives of the equity when approaching the issue.

In principle, effort sharing can be implemented in two different ways: by negotiating among the parties or by using a systematic methodology to quantify the effort required from the parties. In practice, the participation of a country is a political decision and use of various methodologies can be used to inform the negotiations.

A combination of a systematic methodology and negotiations was used in the EU's internal effort sharing. A common emission reduction target of the EU15 under the Kyoto Protocol is to reduce its emissions by 8% from the level of 1990. The internal effort sharing between Member States was negotiated based on the Triptych method developed by the University of Utrecht (Blok et al. 1997). Only CO_2 emissions from fossil fuel combustion activities were considered and three different emission categories were distinguished in the original version: the power sector, energy-intensive industries, and all the rest together as the 'domestic sector'. The selection of these categories was based on a number of differences in national circumstances raised in the negotiations that were relevant to emissions and emission reduction potentials: differences in the fuel mix for the generation of electricity, in the economic structure and in the competitiveness of internationally-oriented industries. The Triptych approach has been extended on a global scale to include more sectors and gases, and Triptych version 6.0 is described in detail in (Phylipsen et al. 2004).

The fundamental problem with effort sharing tools is the trade-off between the ability to consider national circumstances and a straightforward and transparent structure, which is called for from negotiation tools. The Triptych approach is a compromise between both types of desirable features. It lacks essential decision support model features when compared to complicated energy system or economic models, but, thanks to its differentiation by sectors and countries, it is more sophisticated than effort sharing approaches based only on e.g. per-capita emission level, as concluded by Soimakallio et al. (2006).

The description of differences between countries or regions is, however, relatively rough in the Triptych approach. National circumstances or natural resource basis is only reflected on the historic emission level. In addition, cost-effectiveness to reduce emissions or the turnover times of investments are not considered. The lack of connections between sectors may lead to very unrealistic development in certain countries or regions, in particular, in the long run. Due to the above-mentioned causes, the assumptions and results of the Triptych or any other effort sharing approach should be reflected against more versatile energy system and economic models.

This publication presents an impact assessment for applying two relatively sophisticated effort sharing methods – i.e. Triptych and Multistage – on the regional level in ambitious climate scenarios up to 2050. The figures for Triptych and Multistage effort sharing schemes were provided by Ecofys using their Evolution of Commitments (EVOC) tool. The scenario analysis was carried out using the VTT version of ETSAP TIAM, a global TIMES energy system model. The publication provides a perspective on the required amount of emission allowance trading and mitigation costs for the regions under various scenarios, and emission reduction targets together with emission allowances given by the EVOC tool. The publication also provides a rough effort sharing based on equal emission reduction costs per GDP calculated by the TIMES model. In addition, two special considerations, the impact of transaction costs and restricted emission trading, are studied.

2. Key concepts

2.1 Equity and effort sharing

Equitable effort sharing is one of the main principles of the United Nations Framework Convention on Climate Change. Article 3.1 of the Convention states that the parties to the Convention should protect the climate system "on basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities". However, the question of what is actually equitable is ambiguous. Numerous equity definitions have been proposed, and below is a partial list assembled from (Ringius et al. 1998) and (Aldy et al. 2003):

- Egalitarian equity – *equal emissions per capita*
- Sovereign equity (or Proportional equity) – *equal reductions from, e.g., 2000*
- Horizontal equity – *equal net change in welfare, e.g. in GDP*
- Vertical equity (or Comparable effort) – *equal net cost, e.g., relative to GDP*
- Equal responsibility – *effort based on historical emissions.*

As a result of differing views on equity, a number of different methods for effort sharing have been proposed. The proposals range from very simple, such as equal emissions per capita or grandfathering (sovereign equity), to more sophisticated ones, such as the Triptych and Multistage approaches, which are analyzed in this study. While defining emissions allocated to different countries, there is, however, a dilemma between transparency and detail. A more detailed and sophisticated model can better take into account different national circumstances while measuring the welfare effects or costs to the countries from the mitigation efforts, but, at the same time, the effect of different assumptions and parameters in the model on the resulting emission allowances are obscured.

Some quantitative assessments of different effort sharing methods have been made, such as (Miketa and Schrattenholzer 2006) and (Vaillancourt and Waaub 2004). However, these studies have mostly analyzed simpler effort sharing methods, such as equal emission per capita and equal carbon intensity. This study, therefore, aims to assess the effort sharing using a simple but transparent EVOC tool with a detailed but opaque TIMES energy system model in long-term scenarios up to 2050.

We primarily take the viewpoint of vertical equity and measure the comparability of efforts through net mitigation costs per GDP, based on the results of the TIMES model. Using the mitigation costs per GDP as the measure of effort implicitly assumes a logarithmic utility from GDP per capita, and thus a decreasing marginal utility, so that the developed countries would commit to higher costs per capita on absolute terms than the developing countries. It should be noted, however, that, as in any long-term scenario or forecasting study, the results on regional mitigation costs include large uncertainties, and should be taken as indicative.

2.2 Emission trading

The aim of the emission trading system is to achieve cost-efficiency through emission trading. This is based on the fact that different regions have different potentials for emission reductions with different costs. To achieve a cost-effective solution to the mitigation problem, emissions should be reduced in regions with least costs, and these regions could gain profit for doing so.

This is schematically shown in Figure 1, where two regions have differing cost curves and targets for emission abatement. The regions reduce their emissions to a level where their combined reductions equal the total reduction target and the price of reducing an additional tonne of emissions, the marginal price of emissions, is the same in both regions. Then the region whose reductions fall short of the actual reduction target assigned for that region buys emission allowances from the region that exceeded its reduction requirement. How the overall reduction target is distributed between the regions does not affect the actual emission reductions carried out by the regions, only the amount of emission allowances transferred between the regions. Therefore, assuming perfect allowance markets, the initial allocation of emission allowances is, in effect, solely about balancing the mitigation costs of different countries via a new transferable paper of value introduced to the market.

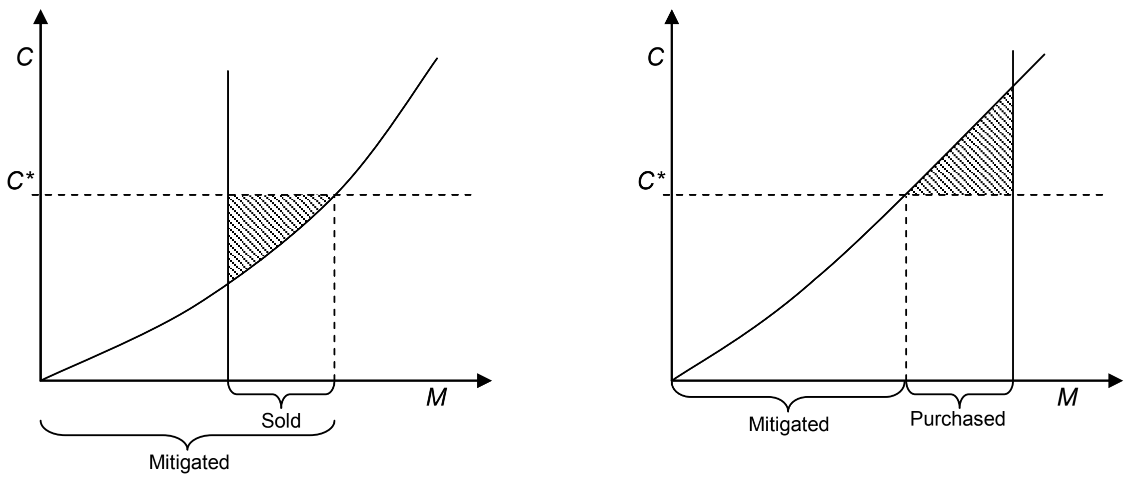

Figure 1. Schematic diagrams of marginal abatement curves and allowance trading in two regions, where M equals the mitigation effort of the region, C the marginal cost and C the market price of allowances. The solid vertical line represents the mitigation target of the country.*

Apart from the total cost of a region, another relevant measure of effort would be the welfare loss resulting from the emission reductions. The TIMES modelling approach would also enable rough estimation of welfare changes in different regions, giving rise to consideration of horizontal equity. However, effort sharing through the allocation of emission allowances does not have a direct impact on the welfare loss of a country under the perfect markets assumption. It would have a secondary effect through an increase in consumers' abilities to pay if more allowances are allocated to a country. This is, however, a much more complex issue and cannot be modelled with the partial equilibrium approach used in this study. With imperfections in the allowance market, the initial allocation would directly affect the welfare loss of a single country.

Caution must be exercised when interpreting the results concerning regional welfare losses. The model setup does not differentiate regions in any way with regard to the price elasticity, and, due to regional differences in consumer preferences and consumers' capacity to pay, the price elasticities would most likely behave in different magnitudes in different regions. However, projecting these regional differences in any justified way up to fifty years into the future would be a daunting task. Therefore, the welfare loss figures are to be taken more as an illustrative result than exact, even when considering the uncertainties in long-term scenario analysis.

3. Models and modelling tools

Two different models were used in this study. First, Evolution of Commitments (EVOC), a transparent but simplified effort sharing tool, is used to quantify the initial emission allocation of different countries with the Triptych and Multistage effort sharing schemes. Possible future scenarios with the different emission allocations are then analyzed with the more sophisticated but complex ETSAP-TIAM, a global integrated assessment model of the TIMES family. Although the TIMES model is well documented, fully consistent and the input data can be made available upon request, the vast size and relative complexity of the model may render the model non-transparent to the reader.

As we are assuming perfect allowance markets, the result is a number of scenarios, otherwise similar but each with a different initial allocation of emissions and therefore different emission trade flows and regional costs or revenues from the trading. The results indicate both how well a simplified model can take into account the relevant characteristics of the countries as well as general paths and issues that arise with climate change mitigation and effort sharing.

3.1 EVOC

This section describes the EVOC tool version 8, developed by Ecofys, that is used to quantify emission allowances under the various approaches in this publication. It includes emissions of CO_2, CH_4, N_2O, hydroflourocarbons (HFCs), perflourocarbons (PFCs) and sulphur hexafluoride (SF_6) for 192 individual countries. Historical emissions are based on national emissions from IEA and the EDGAR database. Future emissions are based on the IPCC Special Report on Emissions Scenarios (IPCC 2000). The greenhouse gas emission data for 1990 to 2003 is derived by an algorithm that combines emission estimates from various sources.

We first collected historical emission estimates by country, by gas and by sector from the following:

1. CO_2 emissions from fuel combustion as published by the International Energy Agency. The latest available year is 2003 (IEA 2005a).
2. CO_2, CH_4, N_2O, HFC, PFC and SF_6 emissions from the EDGAR database version 3.2 available for 1990 and 1995 (Olivier and Berdowski 2001).[1]

[1] For CH_4 and N_2O, the values of EPA are largely based on the EDGAR database (1990 and 1995), but extended to the year 2000.

Future emissions are derived from the MNP/RIVM IMAGE implementation of the SRES scenarios (IMAGE team 2001).

The datasets vary in their completeness and sectoral split. We first defined which of the sectors provided in the datasets correspond to 7 sectors. This definition is provided in Table 1. Note that CO_2 emissions from the IEA do not include process emissions from cement production. Hence, if IEA data is chosen, process emissions from cement production are not included.

For each country, gas and sector, the algorithm completes the following steps:

1. For all data sets, missing years in between available years within a data set are linearly interpolated and the growth rate is calculated for each year step.
2. The data source is selected, which is highest in hierarchy and for which emission data is available. All available data points are chosen as the basis for absolute emissions.
3. Still missing years are filled by applying the growth rates from the highest data set in the hierarchy for which a growth rate is available.

As future emissions are only available on a regional basis and not country-by-country, the resulting set of emissions is then extended into the future by applying the growth rates of the respective sectors and gas of the region to which the country belongs.

Table 1. Data sources and definition of sectors.

	Edgar 3.2 database		**IEA**	
	Regional:	**country by country**	**Regional:**	**country by country**
	Temporal:	**1990 and 1995**	**Temporal:**	**1970 and 2003**
	Gas:	**CO2, CH4, N2O, HFCs, PFCs, SF6**	**Gas:**	**CO2**
Industry				
	F10	Industry	3T	Other Energy Industries
	F30	Other transformation sectors	401	Iron and Steel
	B10CH4N2O	Biofuel industry CH4 N2O	402	Chemical and Petrochemical
	B30CH4N2O	Biofuel charcoal production CH4 N2O	403	Non-Ferrous Metals
	I10	Iron and steel	404	Non-Metallic Minerals
	I20	Non-ferrous metals	405	Transport Equipment
	I30	Chemicals	406	Machinery
	I40	Building materials	407	Mining and Quarrying
	I50	Pulp and paper	408	Food and Tobacco
	I60	Food	409	Paper, Pulp and Printing
	I70	Solvent use/ Miscellaneous	410	Wood and Wood Products
	I80	Transport evaporation	411	Construction
	I90	Miscellaneous industry	412	Textile and Leather
	F60	Non-energy use and feedstocks	413	Non-specific Industry
			414	Non-Energy Use Ind/Transf/Energy
If the IEA data set is chosen, process emissions from industry (e.g. from cement) are not covered				
Electricity				
	F20	Power generation	11	Public Electricity Plants
	B20CH4N2O	Biofuel power generation CH4 N2O	12	Public CHP Plants
			13	Public Heat Plants
			14	Own Use in Electricity, CHP and heat plants
			21	Autoproducer Electricity Plants
			22	Autoproducer CHP Plants
			23	Autoproducer Heat Plants
Domestic				
	F40	Residential, commercial and other sectors	5T	Transport
	F51	Transport road	6T	Other Sectors
	F54	Transport land non-road	*MB Memo:*	*International Marine Bunkers*
	F57	Transport air (international and domestic)	*AB Memo:*	*International Aviation Bunkers*
	F58	*Transport international shipping*		
	B40CH4N2O	Biofuel residential CH4 N2O		
	B51CH4N2O	Biofuel transport road CH4 N2O		
	C10	HFC-byprod.		
	C20	HFC use		
	C30	PFC-byprod.		
	C40	PFC use		
	C50	SF6 use		
Sectors in italics are excluded when the user chooses to exclude international transport				
Fossil fuel production				
	F70	Coal production	7T	Differences due to Losses and/or Transformation
	F80	Oil production, transmission and handling		
	F90	Gas production and transmission		
	F95	Fossil fuel fires		
Agriculture				
	L10	Fertiliser use		
	L15	Rice cultivation		
	L20	Enteric fermentation		
	L30	Animal waste management (confined N2O, all CH4)		
	L50	Crop production		
	L60	Animal waste management (deposited on soil- N2O)		
	L71	Atmospheric deposition		
	L75	Leaching and run-off		
LUCF				
	L41	BB-Deforestation		
	L42	BB-Savanna burning		
	L43	BB-Agricultural waste burning		
	L44	BB-Vegetation fires		
	L45	BB-Deforestation post burn effects		
Waste				
	W10	Landfills		
	W15	Humans/pets		
	W20	Human water treatment		
	W30	Human waste disposal		
	W40	Waste incineration		
	W50	Miscellaneous waste handling (hazardous waste)		
CO2 emissions from Biomass burning (EDGAR sectors B10 to B51) are not included as they are not to be included in the national totals according to the IPCC guidelines and the UNFCCC reporting guidelines)				

The user can specify the following:

- Whether the emissions are determined on the basis of the hierarchy (default setting for this project) or are based exclusively on the EDGAR database
- Whether to consider only CO_2, the group of CH_4 and N_2O or the group of CO_2, CH_4, N_2O, HFC, PFCs and SF_6 (default setting for this project)

- Whether the analysis should
    - exclude emissions from land use change and forestry (default setting for this project)
    - include emissions from land use change and forestry from EDGAR
- Whether international aviation and marine transport is
    - included (default setting for this project) or
    - excluded.

For population, GDP in purchase power parities and electricity demand, the country base year data was taken from (UN 2002) and (IEA 2002) and extended into the future applying the growth rates from the IMAGE model for the region to which the country belongs.

Emissions until 2010 are estimated as follows: It is assumed that Annex I countries implement their Kyoto targets by 2010. It is assumed that the reductions necessary to meet the Kyoto target are achieved equally in all sectors. In 2010, the level of the domestic sector is taken from the relevant reference scenario. The level of the other sectors are taken from the reference scenario and reduced so that the Kyoto target is met. The years from the last available year to 2010 are linearly interpolated. All non-Annex I countries follow their reference scenario until 2010.

Additionally, the user can select the following:

- Whether the USA in 2010 reaches
    - Its Kyoto target
    - Its national target, which we interpreted as a 23% increase in total emissions from 1990 to 2010 (default setting for this project)
    - Its reference emissions
- Whether all other Annex I countries in 2010 reach
    - Their Kyoto targets
    - The lower of their Kyoto target and their reference scenario (default setting for this project)
    - Their reference emissions.

As a default setting, all Annex I countries are assumed to reach the lower of their Kyoto target and their reference scenarios in 2010. Only the USA is assumed to reach only its national target, which we interpreted as a 23% increase in total emissions from 1990 to 2010. All non-Annex I countries follow their reference scenario until 2010. After 2010, the emission allowances per country are calculated according to the approaches.

A limitation of the tool is the unknown future development of emissions of individual countries. Here we have used the IPCC SRES scenarios, the standard set of future emissions scenarios, as a basis. They provide a broad range of storylines and therefore a wide range of possible future emissions. We cover this full range of possible future emissions, economic and population development in a consistent manner. But the SRES scenarios are only available at the level of up to 17 regions (as in the IMAGE implementation) and scaling them down to individual countries introduces an additional element of uncertainty. We applied the growth rates provided for 17 world regions to the latest available data points of the individual countries within the respective regions. So, on the level of regions, we cover the full-range uncertainty about future emissions. When again aggregating the regions, the effect of downscaling cancels out. But the full level of uncertainty is not covered on the national level as substantial differences may exist for expected growth for countries within one of the 17 regions.

The future reference development of emissions, economic and population is affected by the starting values (which is data available from the countries or other international sources and which can be substantially different for countries in one region) and the assumed growth rates (which are derived from the 17 regions).

The assumed growth rates may affect the results of countries to a different extent. Some countries are less affected as they dominate their regional group, such as Brazil, Mexico, Egypt, South Africa, Nigeria, Saudi Arabia, China and India. It is for the second or third largest countries in a region or for members of an inhomogeneous group that this method may lead to an over or underestimation of the future development.

The second or third largest countries in a region are, e.g., Argentina, Venezuela, United Arab Emirates and South Korea. In the Contraction and Convergence approach, the error would be small as these countries only follow their reference scenario until 2010 and converge afterwards. For Common but Differentiated Convergence and Multistage, the downscaling method may influence the time of participation. But the countries listed above would all participate at the earliest possible moment, based on their already high per capita emissions. In the Triptych approach, growth in industrial and electricity production and a reduction below reference for agriculture is used, which may be affected by the downscaling method.

Members of an inhomogeneous group would be the countries of South East Asia, which includes Indonesia and the Philippines as lower-income countries, and Malaysia, Singapore and Thailand as higher-income countries. Here the growth is averaged over the region, probably underestimated for Indonesia and the Philippines and overestimated for Singapore. The dominant element here is the starting point. The low per capita emissions of the Philippines and Indonesia lead to their late participation, while the high per capita emissions in Malaysia, Singapore and Thailand lead to their immediate participation. In the Triptych approach, growth in industrial and electricity production and a reduction below reference for agriculture is used, which may be affected by the downscaling method.

For Annex I countries, the future reference development is not as relevant since they always participate in the regime on the highest stage and have to reduce emissions independently of the reference development. Future values are only relevant for intensity targets (GDP) or for the Triptych approach (industrial and electricity production).

A different uncertainty is introduced since our future emissions are static, meaning that emissions in non-participating developing countries do not change as a result of ambitious or relaxed emission reductions in developed countries. Stringent reductions could affect emissions of non-participating countries in two ways: there could be increased emissions through migration of energy-intensive industries or decreased emissions due to technology spill-over. Overall, we assume that this effect is small and does not significantly influence the results of this analysis.

3.1.1 Triptych

This approach was originally developed at the University of Utrecht (Blok et al. 1997) to share the emission allowances of the first commitment period within the European Union. It has since been updated and revised (Phylipsen et al. 1998, Groenenberg 2002, den Elzen and Lucas 2003, Höhne et al. 2003, Phylipsen et al. 2004, Höhne et al. 2005, Höhne 2006).

Analogue to the first Triptych approach, the global Triptych approach is a method to allocate emission allowances among a group of countries based on several national indicators.[2] It takes account of the main differences in national circumstances between countries that are relevant to emissions and emission reduction potentials. The Triptych approach as such does not define which countries should participate, but here we have applied it to all countries equally.

If the approach is applied globally, substantial reductions for the industrialised countries, especially those with carbon-intensive industries (i.e. Eastern Europe and Russian Federation), are required. Substantial emission increases are allowed for most

[2] Unlike, e.g., the Multistage approach, which is more a framework of stages that can be filled with different allocation methods for the several stages, or C&C, which is based only on per capita emissions.

developing countries. But for lower concentration targets (e.g. 450 ppmv CO_2), these are rarely above BAU emissions.

The Triptych methodology calculates emission allowances for the various sectors, which are summed to obtain a national target. Only the national targets are binding, rather than just individual sector targets. This provides countries with the flexibility to pursue any cost-effective emission reduction strategy.

The sectors' emissions are treated differently: For 'electricity production' and 'industrial production', a growth in the physical production is assumed together with an improvement in production efficiency. This not only takes into account the need for economic development but also constant improvement in efficiency. For the 'domestic' sectors, convergence of per capita emissions is assumed. This takes into account the converging living standards of the countries. For the remaining sectors, 'fossil fuel production', 'agriculture' and 'waste', similar reduction and convergence rules are applied.

An advantage of the Triptych approach is that national circumstances are explicitly accommodated. It explicitly allows for economic growth at improving efficiency in all countries and aims to put internationally competitive industries on the same level. Furthermore, it has successfully been applied as a basis for negotiating the differentiation of the targets between the EU Member States for the Kyoto Protocol.

On the other hand, the Triptych approach is very complex and requires many decisions and sectoral data, making global application a challenge, and may be perceived as not transparent. Furthermore, agreement on the required projections of production growth rates for heavy industry and electricity may be difficult.

3.1.2 Multistage

As the name suggests, in a Multistage approach countries participate in several stages, with differentiated types and levels of commitments[3]. Each stage has stage-specific commitments with countries graduating to higher stages when they exceed certain thresholds (e.g. emissions per capita or GDP per capita). All countries agree to have commitments at a later point in time. For this analysis, thresholds based on per capita emissions with four stages were applied as follows (e.g. Höhne et al. 2005):

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[3] E.g. Claussen and McNeilly 1998; Gupta 1998; Berk and den Elzen 2001; US-EPA 2002; Blanchard et al. 2003; CAN 2003; Criqui et al. 2003; den Elzen et al. 2003; Gupta 2003; Höhne et al. 2003; Ott et al. 2004; Blok et al. 2005; den Elzen 2005; den Elzen et al. 2005; Höhne et al. 2005; Höhne and Ullrich 2005; Michaelowa et al. 2005; den Elzen et al. 2006.

- ***Stage 1 – No commitments:*** Countries with a low level of development do not have climate commitments. As a minimum, all least developed countries (LDCs) would be at this stage. In the model, countries at this stage follow their reference scenario as no emission reductions are required.
- ***Stage 2 – Enhanced sustainable development:*** At the next stage, countries commit to sustainable development in a clear way: The environmental objectives have to be built into the development policies. Such a first 'soft' stage would make it easier for new countries to join the regime. Requirements for such a sustainable pathway could be defined, e.g. inefficient equipment is phased out and requirements and certain standards are met for any new equipment, or there is a clear deviation from the current policies, depending on the countries. This stage is implemented in the model by assuming countries reduce emissions by a percentage below their reference scenario within 10 years and then follow the reduced reference scenario.
- ***Stage 3 – Moderate absolute target:*** At this stage, countries commit to a moderate target on absolute emissions. The emission level may be higher than the starting year, but it should be below a reference scenario. The target could be positively binding, meaning that allowances can be sold if the target is exceeded but no allowances have to be bought if the target is not achieved. An incentive to accept such a target would be the possibility to participate in emissions trading. To model the group of countries at this stage, a percentage reduction below their reference scenario more stringent than in stage 2 is assumed.
- ***Stage 4 – Absolute reduction target:*** Countries at stage 4 receive absolute emission reduction targets and have to substantially reduce their absolute emissions until they reach a low per capita level (essentially a fifth stage). The whole group of countries reduces its emissions as a certain percentage compared to 1990. The actual contribution of each country depends on its per capita emissions. Countries with high emissions per capita have to reduce more than countries with low emissions per capita. As time progresses, more and more countries enter stage 4.

An advantage of the Multistage approach is the gradual phase-in of countries. Furthermore, it is in line with the UNFCCC spirit, taking into account national circumstances. It is a general framework that can accommodate many ideas and satisfy many demands. It allows for gradual decision making and is trust-building as industrialised countries take the lead. It is compatible with the Kyoto Protocol (reporting and mechanisms).

On the other hand, a Multistage approach can lead to a complex system that requires many decisions and allows for exceptions. This bears the risk that countries enter too late so that some long-term stabilisation options are lost. Furthermore, incentives are needed for countries to participate in a certain stage.

3.2 ETSAP-TIAM

The energy and emission scenarios in the study were formed with the TIAM (TIMES Integrated Assessment Model), which is based on the TIMES (The Integrated Markal-EFOM System) modelling methodology (Loulou et al. 2005), both developed under the IEA's ETSAP (Energy Techology Systems Analysis Program) program. Various models based on TIMES and MARKAL frameworks, the latter being the predecessor of TIMES, have been successfully utilized in over 40 countries in analysis of energy and environmental issues, both in practical policy analysis and in more methodological questions. Documentation on the ETSAP-TIAM and TIMES models in general can be found in (Loulou and Labriet 2008) and (Loulou 2008), or (Loulou et al. 2005).[4]

Generally, two types of models have been used for assessing the implications of climate change mitigation: either top-down general equilibrium macroeconomic models, which assess the whole economy with a limited description of the energy system, or bottom-up models, which only focus on the energy system, thus providing increased accuracy on this portion of the economic system. The TIMES family of models are linear partial equilibrium models that calculate the market equilibrium for the described economic sectors and commodities through the maximization of the total discounted economic surplus. The models assume perfect markets and unlimited foresight for the calculation period.

The energy consumption in the TIAM model is based on external projections of the growth of regional GDP, the population and the volume of various economic sectors. These drivers and IEA energy statistics for a given base year, in this case 2000, are the basis for future projections of the consumption of different energy services, such as road passenger transportation, steel demand or residential heating. In order to satisfy the demands, the model contains estimates of different energy resources and potentials, and a vast number of technology descriptions for energy production, transformation and end use – including data on investment and operation costs, efficiencies and, sometimes, market potentials – and a number of other elements, such as user-defined constraints and international trade links. The resulting energy system is schematically depicted in Figure 2. With some 60 different end-use demand types, 1500 present and future energy technologies, 15 geographical world regions and a calculation period up to 2070, the model turns into an extensive linear programming problem with 500,000 rows and 700,000 variables with the current implementation.

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[4] More information on TIMES and MARKAL model can also be found at http://www.etsap.org.

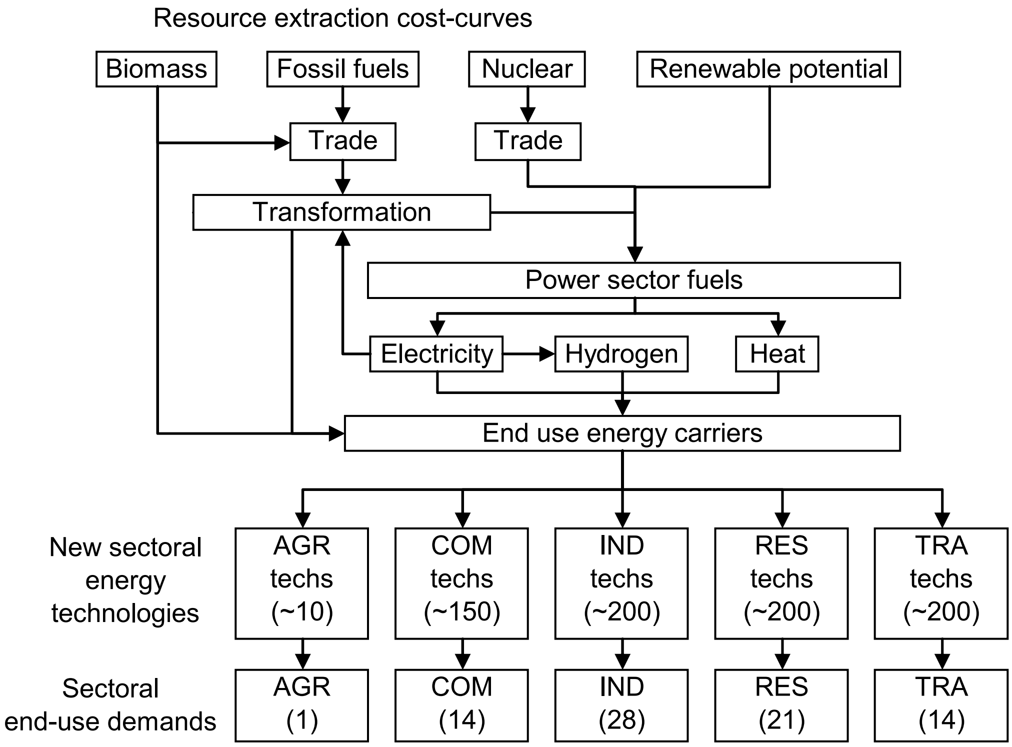


Figure 2. Schematic diagram of the energy system in the TIAM model. The numbers in parentheses represent the number of technologies and demand types.

For each economic background scenario – A1, A2, B1 and B2 – a baseline scenario without any emission constraints was first calculated, serving as a reference point for the emission reduction scenarios. When an emission reduction scenario is calculated, the demand of each end-use energy service is allowed to deviate from the projection, depending on how the price of the service changes from the baseline. In the case of emission reductions, this elasticity of demands lowers the consumption of energy services to some extent, resulting from the restrictions on using low-cost polluting alternatives in the energy production chain.

The geographical division into 15 world regions in the TIMES model is presented in Table 2. The presentation of regions in the table and in the result figures are arranged so that the Annex I regions are first and non-Annex I regions second, with both groups sorted according to their emissions in 2000.

Table 2. Geographical region division in the TIMES model.

Region code	Countries included in the region
USA	United States
WEU	Western Europe (EU-15, Iceland, Malta, Norway, Switzerland)
FSU	Former Soviet Union (includes the Baltic states)
EEU	Eastern Europe
JPN	Japan
CAN	Canada
AUS	Australia-New Zealand
CHI	China (includes Hong Kong, excludes Chinese Taipei)
CSA	Central and South America
ODA	Other Developing Asia (includes Chinese Taipei and Pacific island)
AFR	Africa
IND	India
MEA	Middle-East (includes Turkey)
MEX	Mexico
SKO	South Korea

4. Scenario setup

Evidently, the crafted scenarios are a result of the underlying assumptions. As the scenarios are not accurate predictions but a possible and coherent picture of the future, in order to understand and interpret the results one has to bear in mind how the observed phenomena are driven by the assumptions. This chapter intends to highlight the relevant features behind the scenarios.

4.1 Background assumptions and projections

Apart from the emission targets, the main assumptions defining the scenarios are projections of economic and demographic growth as well as projections of technological progress and resource estimates. Due to the size of the TIMES model, complete reporting of all model parameters is not possible in a research report. However, this section illustrates some of the main assumptions and their sources.

Economic and population projections up to 2100 in EVOC were based on the IMAGE 2.2 (IMAGE team 2001) implementation of the IPCC SRES scenarios (IPCC 2000). In order to ensure similar background development, the socio-economic drivers behind energy demand in TIMES were adjusted to reflect the same GDP and population projections. The background developments are tagged as A1, A2, B1 and B2, and assume different storylines on globalization and material/economic and social/environmental development. However, due to the very different nature and detail of the models, these differences were not incorporated in the TIMES model; the different projections were merely used as sensitivity analysis to provide information on possible variations in the resulting scenarios.

The main driver behind energy demand in TIMES is GDP growth, shown in Figure 3 in global PPP-corrected terms for the four economic scenarios. Economic growth is the main driver behind many energy-consuming activities such as industrial production and transportation, especially international transportation. Therefore, larger economic growth clearly implies larger energy use growth. As the potential for inexpensive ways of producing clean energy is limited, a larger energy demand also implies a need to use more expensive technologies in order to satisfy the demand while keeping emissions low. Therefore, economic growth has direct effects on mitigation costs.

Of the growth projections used, scenario A1 has the largest growth pace, globally 3.9% per year on average between 2000 and 2020, while A2 has the lowest, 2.8% p.a. in the same period. Regionally, the growth levels were quite uniform, although growth was slightly larger with B2 than with B1 in some regions, as can be seen in Figure 4. The regions in the TIMES model are arranged so that the Annex I regions are on the left and non-Annex I regions on the right, with both groups sorted according to their emissions in 2000.

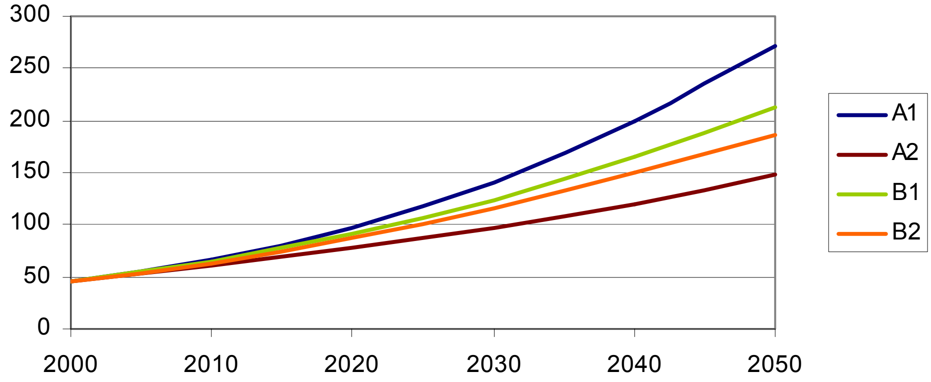


Figure 3. Global GDP projections [Trn. US$2000 PPP] used in the four baseline scenarios.

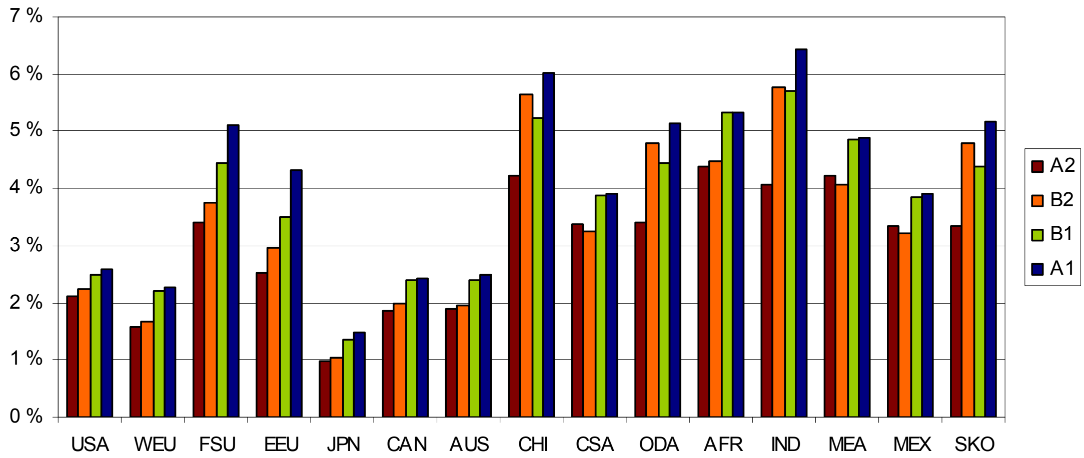


Figure 4. Regional average annual GDP growth between 2000 and 2020 used in the four baseline scenarios.

Assumptions on future technologies, their costs and potentials, and resource estimates evidently have direct implications on how a certain emission target could be reached. The technology and resource estimates for the TIMES model are presented in more detail in (Syri et al. 2008), but brief descriptions are also provided here.

Bioenergy potentials are generally very uncertain and interconnected with other issues, as the food price shocks – partially resulting from current biofuel production – have already shown. The potentials cited by IPCC (IPCC 2007b), based largely on (Hoogwijk 2004), have a range of 129 EJ/a – 411 EJ/a in 2050, although the high end of the potentials can be very optimistic. The amount of bioenergy used in the scenarios is, however, close to the low end of the IPCC figures.

Regional wind energy potentials are split into five onshore and offshore classes, with wind conditions, and are based on estimates by Risø, a Danish research laboratory, the US DOE National Renewable Energy Laboratory (NREL) and Stanford University. A total wind power capacity of 2000 GW was estimated, of which 300 GW in Western Europe, 800 GW in the USA and 300 GW in China. The costs were based on IEA R&D Wind project and learning curve models, resulting in 5–25% lower costs compared to the near future estimated by the IEA in (IEA 2005b). Also, a market penetration limit of 35% from all electricity production was used as the need for greater flexible generation and transmission grid upgrades grows with large amounts of variable wind production in the grid.

Solar power (photovoltaic) in the future was assumed to face substantial cost reductions from the current costs for nominal power of around 5000 \$/kW to levels around 1000–2000 \$/kW by 2050. However, when compared to other electricity production technologies, the competitiveness of solar power is dragged down by the low activity factors and shorter technical lifetime. The activity factors were defined seasonally and by separating day and nighttimes for different regions. As a result, the overall activity factors were around 20%, roughly a quarter compared to large power plants. Taking into account the lifetime, roughly a half from larger power plants, the cost of solar electricity rises to considerably high levels.

Carbon capture is available for a range of processes in the TIMES model, including electricity, heat and steam generation with coal, natural gas or biomass, and in clinker production, with cost and efficiency estimates based on IEA studies (IEA 2004, IEA 2006). Storage potentials have been adopted from a number of literature sources, including the IEA Energy Technology Perspectives project, EMF-22 of Stanford University, the US Environmental Protection Agency (EPA) and IPCC. The most feasible options, storage in depleted gas and oil fields and enhanced oil and coal bed methane recovery, have a cumulative potential of 2180 Gt CO_2, roughly 75 times the CO_2 emissions in 2000. Except for enhanced oil recovery, the technology is still largely in the demonstration phase and thus it should be kept in mind that the cost reservoir estimates are very uncertain.

Hydro and nuclear (fission) power both have small potential for increased capacity from the baseline scenarios. The technical potential for hydropower was adopted from (WEC 2004), 22 500 TWh in 2050. For nuclear reactors, only conventional reactors using ^{235}U were considered, with supercritical water reactor (SCWR) and pebble-bed modular reactors (PBMR) taken as new designs. Breeder reactors were not considered. Uranium reservoir estimates were based on the so-called red book of the IAEA (OECD 2005). Fusion power was estimated to be available from 2050, but with high investment costs of around 6000 \$/kWh$_e$. It is good to note that the uncertainty regarding the timing of introduction and costs of fusion are very large.

One important group of assumptions was the mitigation options for process emissions. Industrial CO_2 from clinker production could be partially mitigated by using blast furnace slag as a constituent, or using CCS in the clinker production. Industrial N_2O could also be mitigated with very good efficiencies. A number of options for different F-gas options were also included, with potentials ranging from 20% to 50%.

Being a very uncertain issue, differing estimates on costs and technical potentials for the agricultural mitigation options have been given in the literature. The assumptions used in this study are adopted from (US-EPA 2006a) and are very similar to EPA's study for EMF-21 of Stanford University (DeAngelo et al. 2006). Generally, the EPA estimates give agricultural reduction potentials of 18% in 2020 for agriculture with prices up to 200 \$/t CO_2, holding agricultural production constant. These potentials were assumed to grow moderately by 2050. Extreme options having higher levels of potential with prices up to 500 \$/t CO_2 were also included, especially for rice and ruminant CH_4 emissions. These might be interpreted as shifting from rice to other cereals and from bovine cattle to pork and poultry.

4.2 Climatic effects

The climate effects calculated by the climate module of the TIMES model are expressed as the increase in mean global radiative forcing (or equivalent CO_2 concentration) and the increase in mean global temperature. Using different economic baseline scenarios for mitigation scenarios produces slightly differing radiative forcing levels due to the different distributions of different greenhouse gases and the differing lifetimes of the gases in the atmosphere. These differences are, however, altogether minor compared to the uncertainties of the climate response.

Figure 5 illustrates the change in radiative forcing and mean temperature change respectively. The 450 ppm target scenario stabilizes on the levels of 3 W/m^2, which actually equals a level of 485 ppm CO_2-eq, somewhat higher than the initial target stabilization level. With the 550 ppm target, the forcing does not yet stabilize at 2100 but is still increasing with forcing of 3.6 W/m^2, equalling 550 ppm. Therefore, the 550 ppm target would not be met with timeframes beyond 2100 with the modelling approach and parameters used. However, the temperature change depicted in Figure 6 gives more positive results as the 450 ppm target is calculated to converge on levels below 2 °C and the 550 ppm target below 2.5 °C, even on longer timescales.

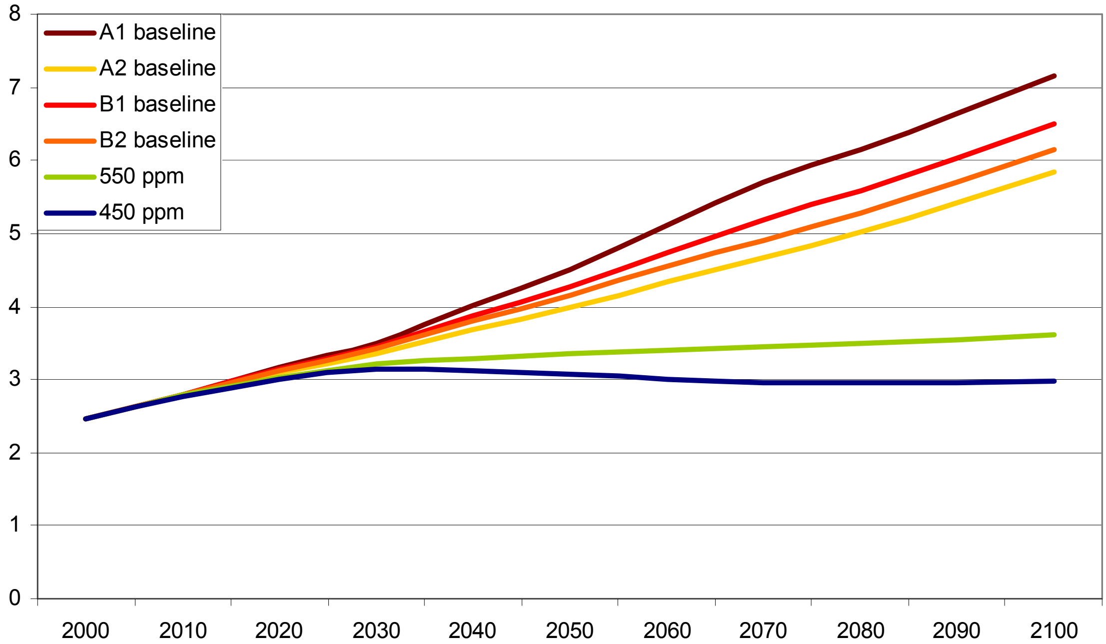


Figure 5. Increase in radiative forcing [W/m^2] from pre-industrial levels in the four different baseline scenarios and with the two reduction targets.

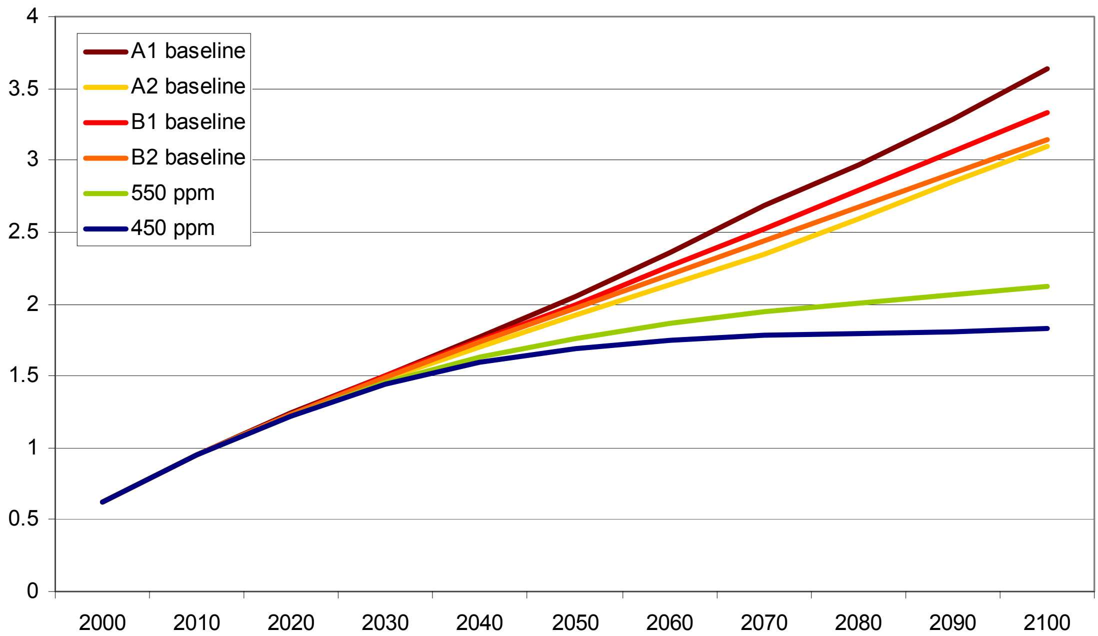


Figure 6. Global mean temperature increase [°C] from pre-industrial levels in the four different baseline scenarios and with the two reduction targets.

4.3 Historical emission inventories

Inventories or statistics on current emissions are far from perfect and subject to uncertainty. As both the effort sharing schemes and scenario projections rely at least indirectly on the estimates of current emissions, the emission inventories play an important role in the study.

Several providers of emission statistics can be identified. Parties to the UN-FCCC are obliged to report their emission inventories, for Annex I parties annually and for the developing countries on a considerably less frequent basis. The IEA publishes a global emission inventory from fuel combustion based on the energy statistics it gathers. The statistics are supplemented with non-combustion emission estimates from the Emission Database for Global Atmospheric Research (EDGAR). Also, EPA has estimated global non-CO_2 emissions (US-EPA 2006b).

The different statistics can exhibit considerable differences in their estimates, especially when regarding developing countries. As an example, Figure 7 presents emissions with the EVOC methodology described in Section 3.1 using UN-FCCC and IEA/EDGAR-based data. Large deviations can be seen from the diagonal line, which represents equal estimates using both sources, and for some individual countries the difference can even be tenfold. Also, for many OECD countries the difference can be close to or over 10%.

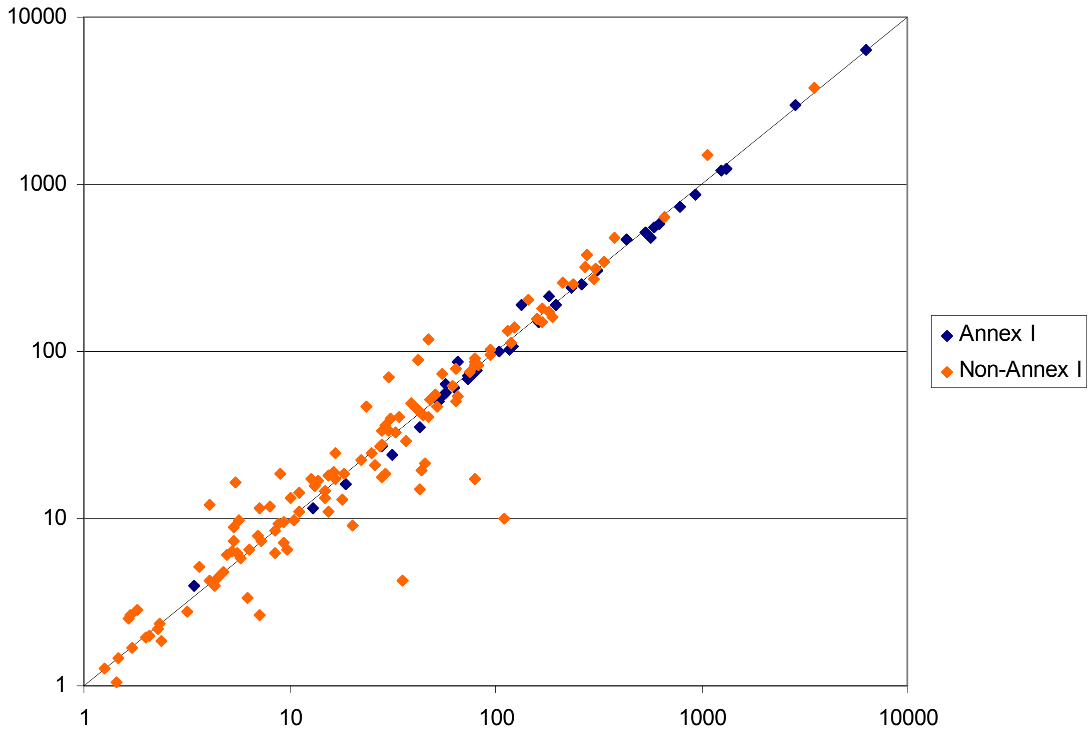


Figure 7. Emission estimates for different countries [Mt CO_2-eq, logarithmic scale] based on UN-FCCC (X-axis) or IEA/EDGAR (Y-axis) statistics.

The differences in historical emissions have a great deal of importance for effort sharing in the future. For example, in the Triptych approach, different reduction targets are applied for different economic sectors. If there are large differences in the sectoral emission estimates, the resulting emission allocations might also vary to a great extent. This study uses the IEA/EDGAR emission dataset as a basis. This decision was made as the dataset is more easily verifiable than the multilayered UN-FCCC data that would have to be supplemented with other datasets, and as the TIMES model is calibrated to represent more closely the IEA data.

4.4 Effort sharing and emission trading

The scenarios assumed two emission targets, labelled as 450 ppm and 550 ppm scenarios from the resulting CO_2-equivalent greenhouse gas concentration, according to (Höhne 2007). Global emission targets and full global emission trading was assumed to start from 2020, whereas only the present targets from the Kyoto protocol were assumed to take place before 2020. The global emission targets were described as presented in Table 3 with a linear reduction between the 2020 and 2050 targets.

Table 3. Emission targets in the study.

Target	Emissions in 2020 relative to 1990 levels	Emissions in 2020 [Mt CO_2-eq]	Emissions in 2050 relative to 1990 levels	Emissions in 2050 [Mt CO_2-eq]
450 ppm	+20%	37 100	–50%	15 700
550 ppm	+30%	39 500	–10%	27 300

The initial allocation of emission allowances in the scenarios was taken from the EVOC results. EVOC does not produce exactly the desired emission level in all SRES scenarios, due to which the results were linearly scaled uniformly across all regions so that the global emissions in 2020 and 2050 were as presented in Table 3. The resulting emission targets relative to 2000 emissions in 2020 and 2050, with the different approaches considered, is presented in Figure 8.

The different approaches result in quite uniform targets for the Annex I regions but rather diverse for non-Annex regions. Annex I regions face reduction requirements between –12% and –47% in 2020 and –64% and –95% in 2050. The 2050 targets are extremely strict if we consider that agricultural CH_4 and N_2O emissions, which have very limited mitigation potential up to prices of 200 \$/t CO_2-eq (US-EPA 2006a), accounted regionally for 7% to 34% of all 2000 emissions in Annex I regions, excluding

Japan, and even 58% in New Zealand (IEA 2005a). This discrepancy between commitments and available mitigation options raises the necessity for flexibility mechanisms such as emission trading.

The reduction targets for non-Annex I regions reflect the state of development of the regions, especially in 2050. The greatest increases are allocated to Africa and India, the least developed regions, while more industrialized regions such as Mexico and South Korea have targets almost comparable to the reductions in Annex I regions. Also, the results from different effort sharing methods and concentration targets are more dispersed than with Annex I regions. Multistage clearly favours the least developed more than Triptych, with India gaining vastly more allowances with Multistage and all apart from India, Africa and other developing Asian countries receiving less. Therefore, as we are assuming perfect allowance markets, the effort sharing method is likely to have a strong impact on the regional mitigation costs of non-Annex I regions.

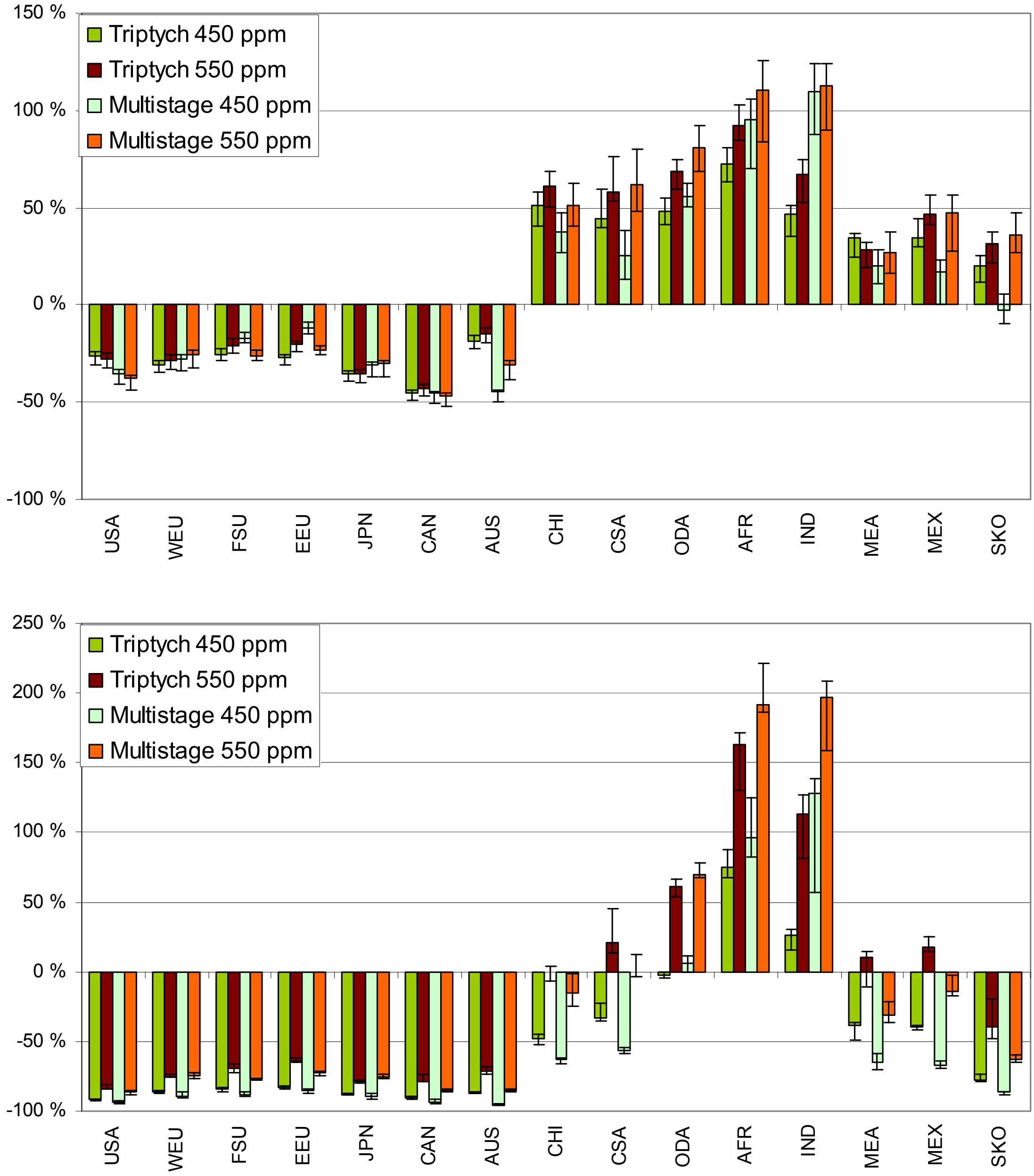


Figure 8. Initial allocation of emission allowances, relative to 2000 emissions, with Triptych and Multistage effort sharing and 450 ppm and 550 ppm targets in 2020 (top) and 2050 (bottom). The ranges are due to the four SRES scenarios.

4.5 Scenarios for performing sensitivity analysis

Two special scenario setups were formed in order to explore the consequences of deviating from our initial perfect market assumptions. The cases considered allowance market imperfections by introducing transaction costs and restricted trade from one important market player. The cases were considered in the B2 Triptych setting with a

550 ppm target. The higher concentration target was chosen as the resulting scenarios were more in the range where the model could provide more reliable results.

4.5.1 The effect of transaction costs

A global allowance market is hardly a perfect market. Information is unlikely to be perfect, some actors might find it difficult or costly to trade in the market and monetary exchange rates might distort the efficiency of the market on a global scale. Also, the market price can be very volatile, providing an incentive for risk averse hedging strategies that are somewhat costlier. Most of these effects are hard to quantify, let alone forecast. Due to this, we evaluate the effects of imperfect markets by imposing a 10$/t CO_2-eq transaction cost to the markets. The resulting schematic figures of marginal abatement curves and allowance trading are depicted in Figure 9.

The effect of transaction cost is analyzed in the scenario with a 550 ppm target in 2020, where the effect of transaction costs is the largest due to the lower price of allowances compared to the 450 ppm target or year 2050.

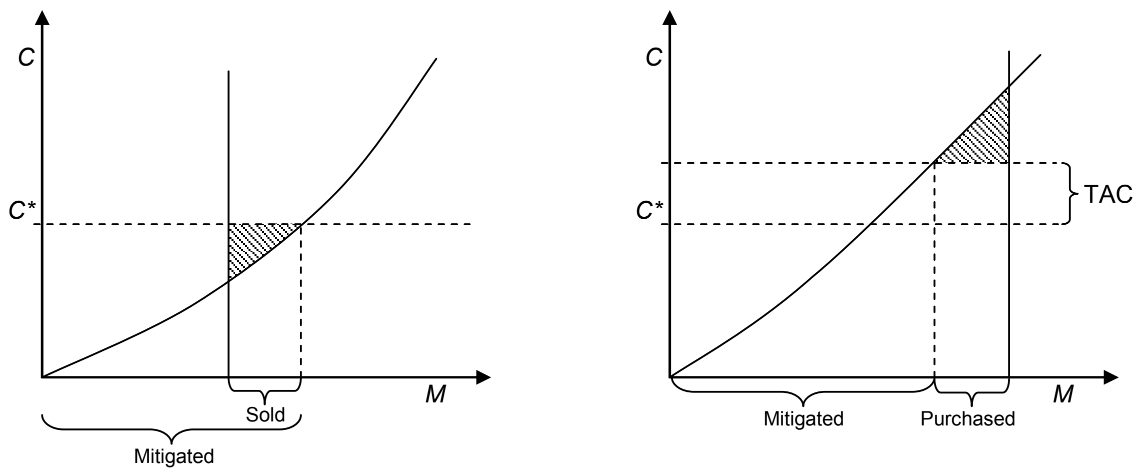


Figure 9. Schematic diagrams of marginal abatement curves and emissions trading in two regions with transaction costs (TAC) for the buyer.

4.5.2 Constraining emission trading

The perfect allowance market assumption is based on the pure economic rationale of the participants, and does not take into account strategic or political incentives. However, these might be important motives for deviating from the cost-optimal strategy. A large impact on global markets would arise if e.g. a large seller, or coalition of net sellers, decides to constrain its allowance sales. Even though it would suffer financially from such a decision, it might still do so to secure energy and commodity prices within its borders. Such a decision might be sensible due to political pressure from rising energy prices, to maintain financial stability or from strategic perspectives to secure production. As an effect, the allowance prices on global markets would be increased due to a greater shortage of allowances.

In this sensitivity study we assume that China, which was identified as the greatest seller of allowances in 2020 with a Triptych 550 ppm allocation, decides not to sell allowances. Also, as the Chinese economy is very dependent on coal, the effect on energy use costs is also more visible. However, any other allowance exporting region could also been have chosen, and the decision to use China as an example was purely based on illustrative purposes.

5. Results

In order to portray what actually happens in the energy system and what measures are taken in order to reach the emission target, the results are presented as follows. First, global emissions projections with breakdowns by sector and emission source are presented, accompanied by cross-sections on regional emissions in 2020 and 2050. As most of the emissions and reduction measures taken deal with energy use, the development of global and regional energy end use and electricity generation are presented. This is followed by a qualitative description of the measures in each economic sector.

After portraying the actions behind the emission and energy projections, we turn to the question of effort sharing. For this, we present some economic consequences from the effort sharing and emission trading schemes used. Our main focus is on regional mitigation costs, and from this viewpoint we also present an allocation of emission allowances that equalizes mitigations costs across the regions relative to their ability to pay. We also consider some effects from market imperfections and present a sensitivity analysis on economic growth projections.

The end of the chapter assesses effort sharing from the viewpoint of Finland. As a rather small country on a global scale, Finland acts as a price taker on the assumed global allowance market. Therefore, it is possible to assess Finland separately from the rest of the world, and, again using the perfect market hypothesis, we can separate the mitigation effort in Finland resulting from the market price of allowances and the mitigation costs from the mitigation effort and initial emission allocation.

5.1 Emission and energy system projections

The TIMES model produces a vast amount of data that describe the actions taken in a single scenario, and it is not possible to report all the results in full detail. Also, as the results consist of eight different scenarios regarding actual energy and emission projections, it would be exhausting to present all the relevant issues in all of the scenarios. Instead, only two scenarios – the moderate growth B2 scenario with 450 ppm and 550 ppm concentration targets – are first presented with detail, and the results depending on the initial allocation – in particular the emission trade and cost projections – are presented for all calculated scenarios.

Figure 10 presents the sectoral breakdown of global GHG emissions from 2000 to 2050 under the 450 and 550 ppm targets in a B2 scenario. Similar regional figures for 2020 and 2050 are also presented in Figure A1 and Figure A2 in Appendix A. Without the reduction measures, the total emissions in the baseline scenario would have risen to over

60,000 Mt CO_2-eq per year in 2050. In the reduction scenarios, the overall emissions start to decrease after 2010 or 2020 respectively for 450 and 550 concentration targets. Most of the reduction measures take place in the electricity generation and industrial sectors. Emissions from transportation are slightly reduced from the baseline until 2030, after which rising demand forces emissions to rise again. Emissions from the residential sector and upstream energy production are reduced slightly while agricultural emissions are mostly left intact.

The emission projections are further broken down into different emission sources in Figure 11. The top figures present process-based and the lower figures combustion-based emissions. It can be clearly seen that most of the reductions arise from energy use, while most process-based emissions continue to rise. Combustion-based emissions account for over two-thirds of current emissions, and, due to this, the results are very similar to those presented in Figure 10. Again, the greatest reduction potential lies in the power and industrial sectors, shifting their relative share from roughly half of all combustion emissions in 2000 to 10% in 2050. In process-based emissions, the reductions are carried out in industry, waste management and agriculture, most notably in CO_2 emissions in cement production starting from 2030. Agricultural emissions account for half of process emissions in 2000 and are projected to grow up to 2040, despite the measures taken in fertilizer use, rice cultivation and cattle CH_4 control. With the 450 ppm target, the marginal price of emissions rises to sufficiently high levels in 2050 so that further N_2O reductions in agriculture become feasible.

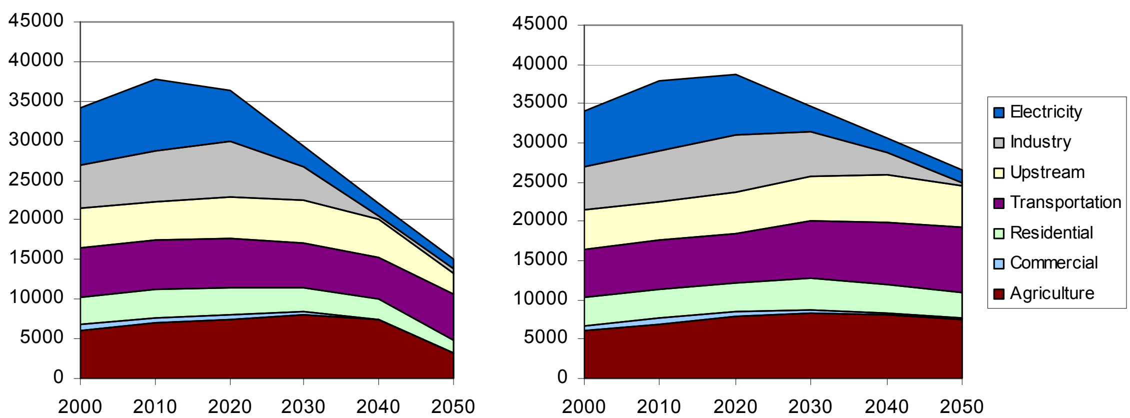


Figure 10. Sectoral breakdown of global total GHG emissions [Mt CO_2-eq] in B2 TIMES scenarios with 450 ppm (left) and 550 ppm (right) reduction targets.

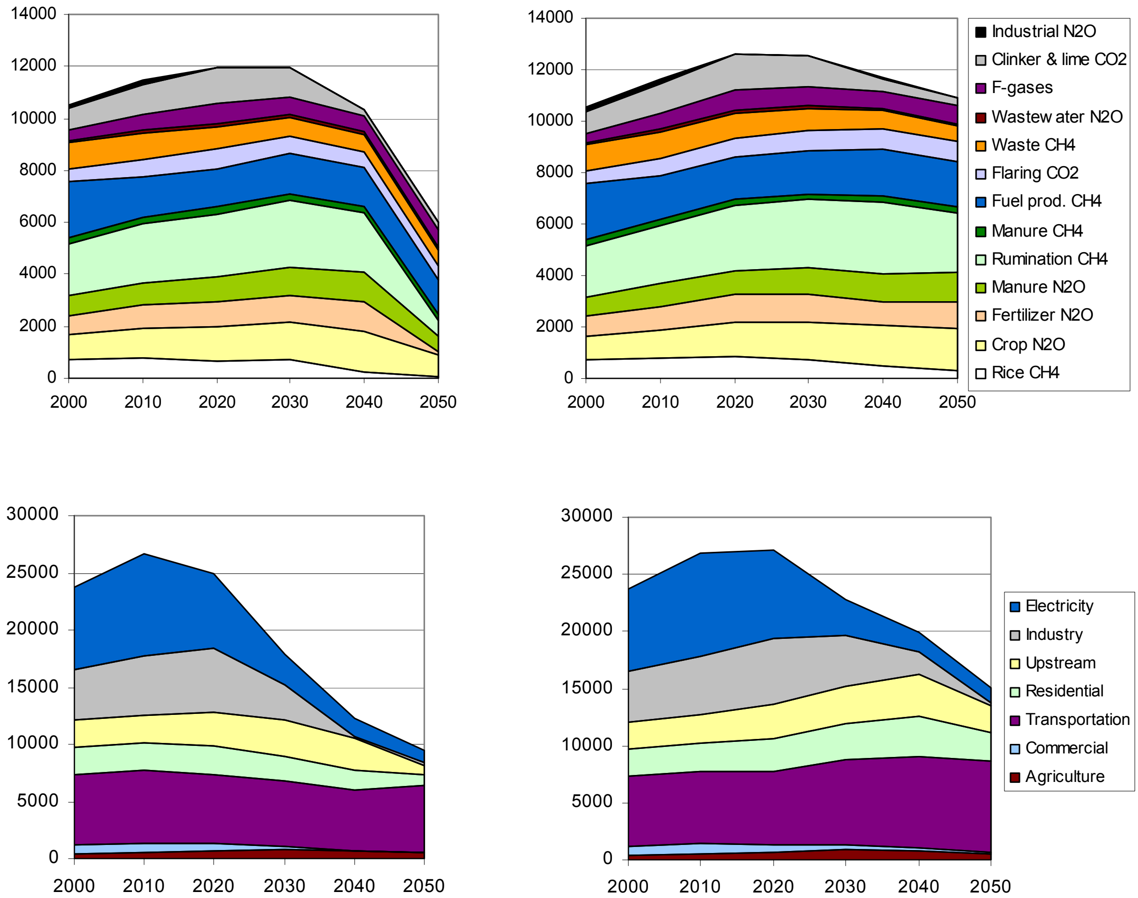


Figure 11. Sectoral breakdown of global process (top) and combustion-based (bottom) GHG emissions [Mt CO_2-eq] in B2 TIMES scenarios with 450 ppm (left) and 550 ppm (right) reduction targets.

Regional and sectoral breakdowns of emissions in 2020 and 2050 with the baseline and both reduction targets are shown in Appendix A. The emissions in Figures A1 and A2 are presented as the fraction of the total emissions of the region in order to remove the effect of the different sizes of the regions. Comparing the emission fractions in the baseline to those in the reduction scenarios, we can regionally assess the ease of reducing emissions. As can be seen from the figures, the emissions are almost the same in the three scenarios in 2020. Only a slight reduction in electricity and industrial emissions takes place in 2020, not very easily seen from Figure A1. In 2050 the differences become more visible. In the baseline, Australia and Central and South America have a larger than average share from agricultural emissions, and this share rises to roughly half of all emissions with the 550 ppm target. Costly mitigation efforts, however, lower their share with the 450 ppm target. A similar pattern can be also seen in the upstream emissions of the Middle East, Former Soviet Union and Mexico.

Global final energy consumption, pictured in Figure 12, only changes slightly in the reduction scenarios. Compared to the baseline, the overall consumption is some 8% lower in 2050 in the reduction scenarios, but this is partially offset by the growing share of electricity in the final energy mix in the long term as the efficiency losses from electricity generation are already accounted for. In addition to electrification, bioenergy and heat use grow and the growing share of coal is replaced by a decreasing trend. Primary bioenergy production reaches a level of 126 EJ/a in 2050 with the 450 ppm target, which is at the low end of the inexpensive bioenergy potential assessed in (Hoogwijk 2004), an optimistic study on which the IPCC estimates are largely based. Gas use rises until 2030 in both reduction scenarios, after which the tightening emissions limit with the 450 ppm target starts to constrain its use. Oil consumption remains relatively stable with the 550 ppm target, while it is slightly decreasing with the 450 ppm target after 2020.

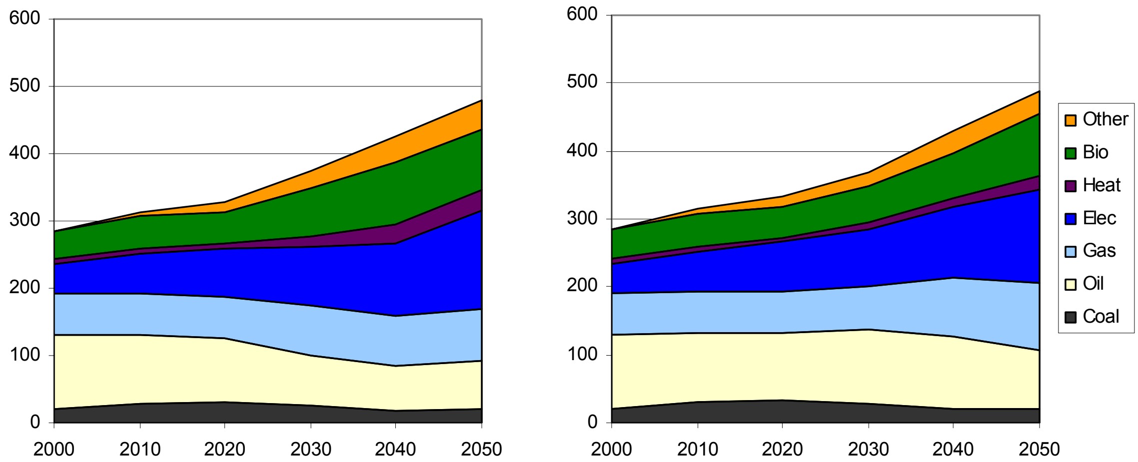


Figure 12. Global final energy consumption [EJ/a] in the B2 TIMES scenarios with 450 ppm (left) and 550 ppm (right) reduction targets.

5.1.1 Electricity

Electricity production faces significant changes in the reduction scenarios when compared to the baseline scenarios. The two reduction targets mainly differ in the adoption of fusion power in 2050, as can be seen in Figure 13 and the figures presented in Appendix B. Both scenarios feature strong adoption of wind power and biomass in electricity production. Hydro and fission power are also increased slightly from the baseline. Coal is phased out after 2010 as no new coal-fired capacity is built with the 450 ppm target, but the existing capacity is used for its remaining lifetime. The 550 ppm scenario only includes minor investments in coal before 2020. Carbon capture and storage with natural gas and coal is used after 2020, and it provides regulating capacity for the variable wind power generation. Overall, these options reduce the emission from electricity generation to very low levels, as indicated in Figure 10.

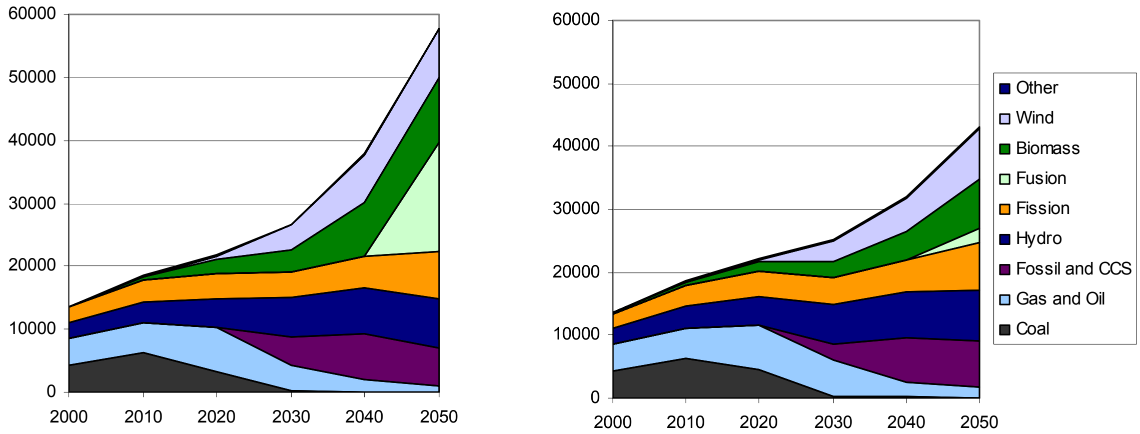


Figure 13. Global electricity generation [TWh/a] in the B2 TIMES scenarios with 450 ppm (left) and 550 ppm (right) reduction targets.

The still quite modest emission reductions in 2020 do not greatly affect the structure of electricity production, and new wind, CCS and hydropower capacity is being installed, mostly after 2020. However, this has considerable effect on the price of electricity in 2020 in regions that use mainly coal-fired power plants, especially China, Australia and South Korea. On the other hand, regions with a large share of hydropower face minimal changes in electricity prices.

The introduction of biomass is the only great change taking place in electricity generation in 2020, mostly in Asia and especially in India. The adoption of biomass firing is largely determined by the regional availability of inexpensive biomass, resulting in large regional differences, which can be seen in Figure B1 in Appendix B. It is extremely important to note the large uncertainties in biomass potentials and production prices. As the production usually competes with food production and forestry, biomass production has multiple connections to other parts of the economic system, which cannot be modelled with the TIMES model.

When interpreting the results up to 2050, it must again be borne in mind that the long-term technology assumptions involve large uncertainties. This is particularly critical with the 450 ppm target, for which the results exhibit a large penetration of fusion power. As the availability of fusion is uncertain, even at this point in time, and the investment costs are assumed to be very high, fusion might well be replaced with other forms of electricity production. This might involve larger market shares of wind, biomass, nuclear or CCS – which are already present in the scenarios – or other technologies – such as solar, tidal or novel technologies – if the costs of these technologies are reduced to lower levels than assumed in this study.

5.1.2 Industry

Around 80% of industrial emissions in 2000 resulted from the burning of fossil fuels, coal, gas and oil in their various forms, the remainder being mostly process-related CO_2 emissions from clinker and lime production. The uses for fossil fuels in industry vary from process heat and fuel for motor drives to use as a reducing agent or carbohydrate feedstock. For the two former uses, a fuel switch to cleaner alternatives, such as natural gas, biomass or electricity, is generally possible, while in the other cases there are fewer alternatives.

As can be seen from Figure 14, the emission reduction efforts mostly affect coal consumption, which is phased out after 2020 and used mainly in conjunction with CCS and in iron and steel production, due to a partial lack of alternatives. Oil and gas consumption remains relatively stable in both reduction scenarios. Biomass gains prominence in steam generation and electricity autoproduction. After 2030, biomass burning is also combined with CCS with both reduction targets, resulting in negative emissions, assuming that the biomass is sustainably produced. The total energy consumption in industry is reduced by roughly 8% in 2020 compared to the baseline due to better energy efficiency, leaving total industrial output down 2–3% from the baseline. However, the rising carbon price affects production in the long run, hitting the production of steel and minerals hardest. On average, industrial production is 10–12% lower in the reduction scenarios in 2050 compared to the baseline.

Process emissions are reduced in increasing amounts towards 2050. N_2O emission reductions using thermal destruction and catalytic reduction respectively in adipic and nitric acid industries are one of the first mitigation measures taken. Blended cement production gains market share from Portland cement, and in 2030 all blast furnace slag produced by the iron and steel industry is used in cement production, reducing the production of clinker. CCS in clinker production is started after 2030, substantially reducing the process CO_2 from clinker production.

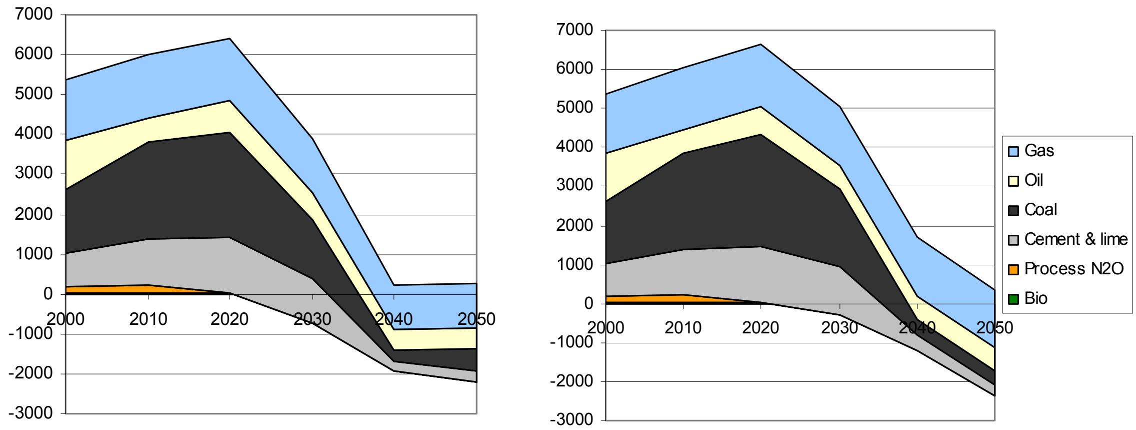


Figure 14. Industrial GHG emissions [Mt CO_2-eq] in the B2 TIMES scenarios with 450 ppm (left) and 550 ppm (right) reduction targets. Biomass is used in conjunction with CCS, resulting in negative net emissions.

5.1.3 Transportation

Transportation is by far the greatest oil consuming sector, accounting for almost 70% of oil energy end use in 2000. In both of the reduction scenarios, oil use in transportation decreases, gradually with the 550 ppm target and more rapidly with the 450 ppm target. Oil is replaced in road transportation by natural gas, hydrogen – which is first produced from natural gas and later using electricity via hydrolysis – and, to some extent, bioethanol. Gasoline and diesel remain in use in light vehicles, although hydrogen or electric vehicles became more attractive with higher allowance prices. However, improved motor efficiencies and hybrid vehicles keep oil consumption and emissions on a stable level up to 2020, even in the baseline, after which the rising demand starts to offset the improvements. Heavy road transportation mostly shifts to natural gas.

The main obstacle to greater emission reductions was, however, international maritime and aviation, both of which were projected to grow more rapidly than global GDP with an average yearly growth of 4.3% and 3.8% between 2000 and 2020 in the baseline. Both are dependent on oil, and, especially in aviation, kerosene is more difficult to replace with low-emission alternatives than with other modes of transport. Due to this inflexibility, the only option for reducing emissions from international transportation was decreased consumption through demand price elasticity. It is, however, hard to quantify the long-term price sensitivity of international transportation in a globalizing world. In the scenarios, the sensitivity response was assumed to be moderate, but the rising allowance prices in the long term reduced the annual growth from 2000 to 2050 for international navigation and aviation from the levels of 4.1% and 3.8% to 2.2% and 2.1% in the 450 ppm scenario. Even so, around two-thirds of the oil used in transportation was consumed in aviation and navigation in 2050. Also, roughly 30% of all combustion-based emissions presented in Figure 11 were from aviation and navigation in the 450 ppm case.

5.1.4 Agriculture

Agricultural emissions are highly process-related. Roughly half of 2000 emissions were CH_4 from cattle, rice patties and animal manure, over 40% N_2O from croplands and nitrogen fertilizer use, and only a few percent of emissions arose from energy use. Agricultural emissions can generally be seen as very uncertain and rather inflexible, and different emissions are often interconnected with other emission sources. Both emissions and reduction measures also depend on a number of conditions, such as climatic conditions, soil type, timing of actions and types of animal feed, and, therefore, have regional differences.

The development of agricultural emissions in the reduction scenarios from different emissions sources was presented in Figure 11. Measures of CH_4 from rice cultivation and cattle, and N_2O from fertilizer are taken starting either from 2020 or 2030, depending on the reduction target. Also, the overall effect of most measures is only partial, and agricultural emissions tend to continue their growth in the reduction scenarios. Controlling the flooding and organic matter addition to rice paddies provides some mitigation potential, while anaerobic digestion of manure, reduced methane from cattle through dietary practices or the use of antimethanogens, and improved fertilizing practices each provide smaller potentials. Further, more expensive options include N_2O mitigation potential in crop production and cattle manure. As the price of allowances climbs to sufficiently high levels, the production of rice and meat of ruminants might shift to other cereals and to pork and poultry, minimizing the CH_4 emissions from rice paddies and rumination. These are, however, large shifts in the production palette, and this might not be easily conducted very quickly in practice.

For comparison, the IPCC (IPCC 2007b) reports that the technical potential of agricultural mitigation has been assessed to be between 4500–6000 Mt CO_2-eq in 2030 compared to the B2 baseline, but that 89% of this potential is from soil carbon sequestration, thus falling into the LULUCF category and being disregarded in this study. Therefore, in 2030, there would be only 500–650 Mt CO_2-eq technical mitigation potential. The TIMES scenarios resulted in 590 and 650 Mt CO_2-eq mitigation efforts compared to the baseline, being very well in line with the estimates cited by the IPCC. The US-EPA (2006a) has estimated the marginal abatement costs from agriculture to be around 50 \$/t CO_2-eq for a 12% decrease from the baseline in 2020, and after 15% to rise rapidly above 200 \$/t CO_2-eq.

Generally, it can be concluded that agricultural non-CO_2 emissions provide relatively inexpensive but very limited mitigation potential. As the emission sources are very dispersed and concentrated more on rural areas of less developed countries, it is harder to control the emissions and effectively introduce better practices. Also, it is important to note the major uncertainties with agricultural emissions, especially concerning N_2O. These uncertainties are not included in the model framework, and, had the emission constraints induced more mitigation in agricultural emissions, it would have been more difficult to make justified conclusions from the results with any certainty.

5.1.5 Other sectors

Slightly over half of GHG emissions in the residential and commercial sectors in 2000 resulted from energy use in the residential sector, a quarter from CH_4 and N_2O in wastewater and waste management, and a bit less than a quarter from energy use in the commercial sector. The energy mix in the residential sector changes gradually after 2020 as electricity and, especially, district heat gain more share, combined with a decline in biomass use in the developing world. Apart from natural gas, all of the trends were also present in the baseline but were more pronounced in the reduction scenarios. However, the use of natural gas was mixed. Gas use was rising in the baseline scenario with a pace similar to electricity while some of this growth shifted to electricity with the 550 ppm reduction target. With the 450 ppm reduction target, gas use started to decline after 2030, following a similar trend to the rest of the energy system. Resulting from this, only a small fraction of global heating and cooking energy use is covered with fossil fuels in 2050 with the 450 ppm target.

Some landfill CH_4 capture options are taken into use in the baseline as the captured gas can be used as energy, e.g. for heating. In the reduction scenarios, a greater variety of these options are also used, along with increased waste incineration in electricity production. Overall trends in the baseline and reduction scenarios are depicted in Figure 15.

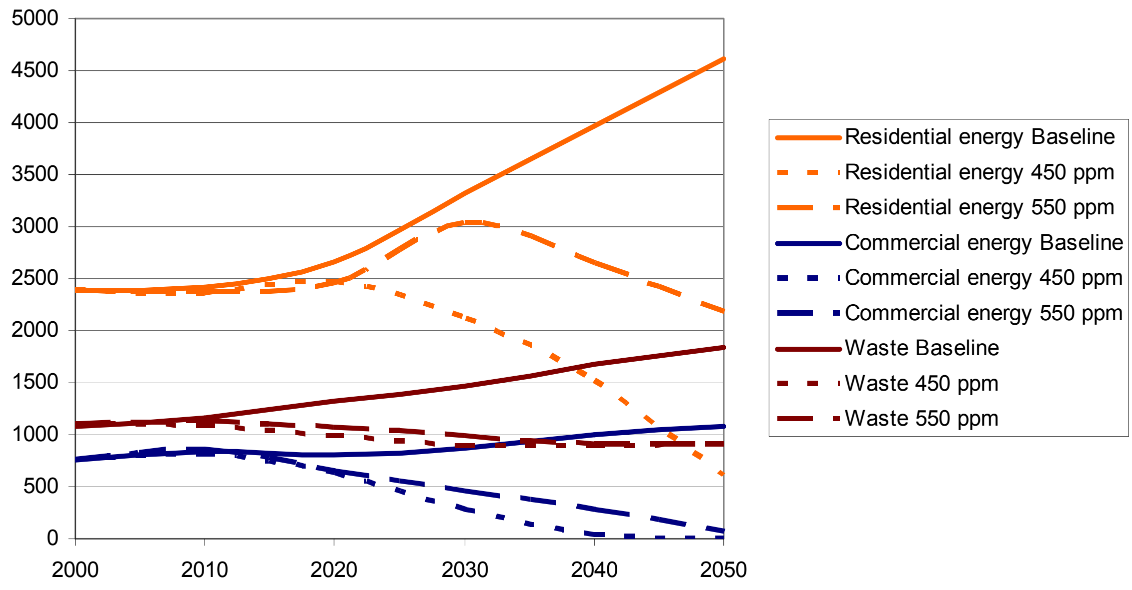


Figure 15. Trends in residential and commercial emissions [Mt CO_2-eq] in the B2 TIMES scenarios.

In upstream energy production, gross emissions decrease from the baseline mostly due to decreased fossil fuel production, most notably coal production. Net emissions are reduced even further due to the introduction of process emissions control and CH_4 recovery options, some of which are already profitable in the baseline scenario.

5.2 Economic effects and effort

This section outlines some economic aspects from the mitigation scenarios. The scenarios use the Triptych approach for effort sharing, which affect the total mitigation costs the countries face through allowance trading. Regional mitigation costs, defined as the difference in energy system costs between mitigation and the baseline scenarios, are presented relative to the regions' baseline GDP for the year 2020 in Figure 16. The costs are split between investment, operation and maintenance (O&M, including commodity extraction) and trade costs, plus welfare loss as the social cost of lost consumption due to the emission reductions. All regions incur losses in some cost classes, which appear as positive costs in the figure, and profits or savings in some classes, which appear as negative costs. The overall net costs were not very large, roughly 0.1% of global GDP.

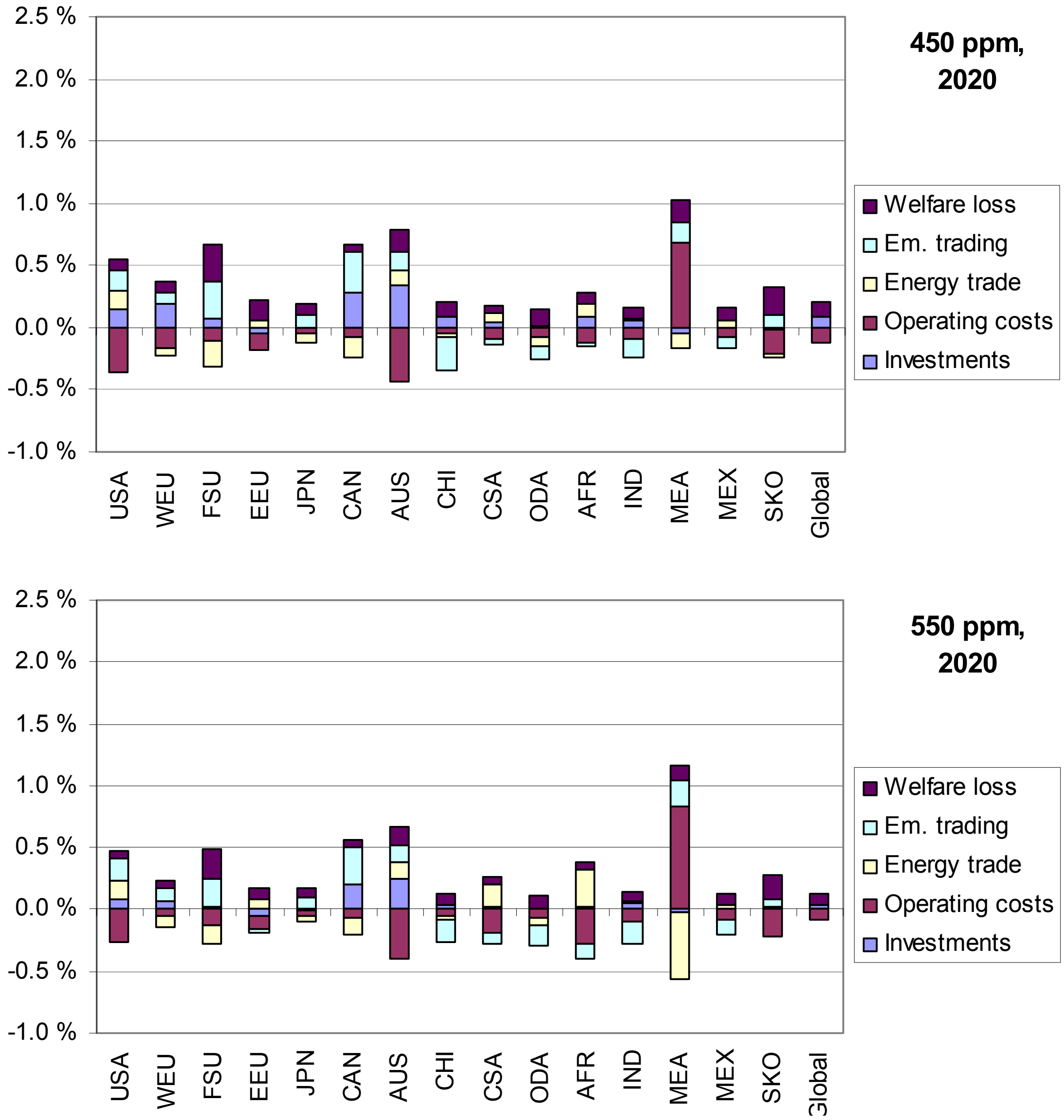


Figure 16. Breakdown of regional mitigation costs per GDP with the Triptych approach in TIMES in 2020 in the B2 TIMES scenarios with 450 ppm (left) and 550 ppm (right) reduction targets.

The distribution of costs in different regions and cost classes are very similar between the two reduction scenarios, only the cost level is slightly higher with the 450 ppm target. The costs on the global scale are relatively modest, around 0.1% of the global baseline GDP in 2020, mostly from increased investment costs, welfare loss and decreased operating costs. Investment costs rise most in electricity generation, where costlier wind turbines, biomass and waste power plants are built instead of coal power. Also, nuclear and hydro gain more capacity. In the transportation sector, investment costs rise mostly due to hydrogen vehicles.

Operational costs are mostly reduced via reduced extraction of fossil fuels. As an exception to this, the Middle East acts in the opposite way by increasing its oil production. As the gulf oil is lighter than the oil pumped in the rest of the world, it is more favourable in climatic terms. However, as the market price of oil is lower in the reduction scenarios than in the baseline, the Middle East is worse off, despite the increased relative competitiveness of its oil. Countries in the region of the former Soviet Union increase their natural gas output and, as a result of the increased gas price, they are better off from resource extraction and trade in the reduction scenarios.

The cost effect of the trade in emission allowances is very uniform with both reduction targets. All Annex I countries are net buyers of emission allowances, resulting in costs between 0.1% – 0.3% from their GDP. In turn, with the exception of South Korea and the Middle East, non-Annex I are able to sell emission allowances with profits between 0.1% – 0.3% from their GDP. The costs and profits are slightly more pronounced with the 450 ppm target as the tighter reduction target implies a higher price for allowances. With the 450 ppm target, the price was between 15 and 26 \$/t CO_2-eq in 2020 in the four economic baselines, while the 550 ppm target resulted in prices between 8 and 19 \$/t CO_2-eq.

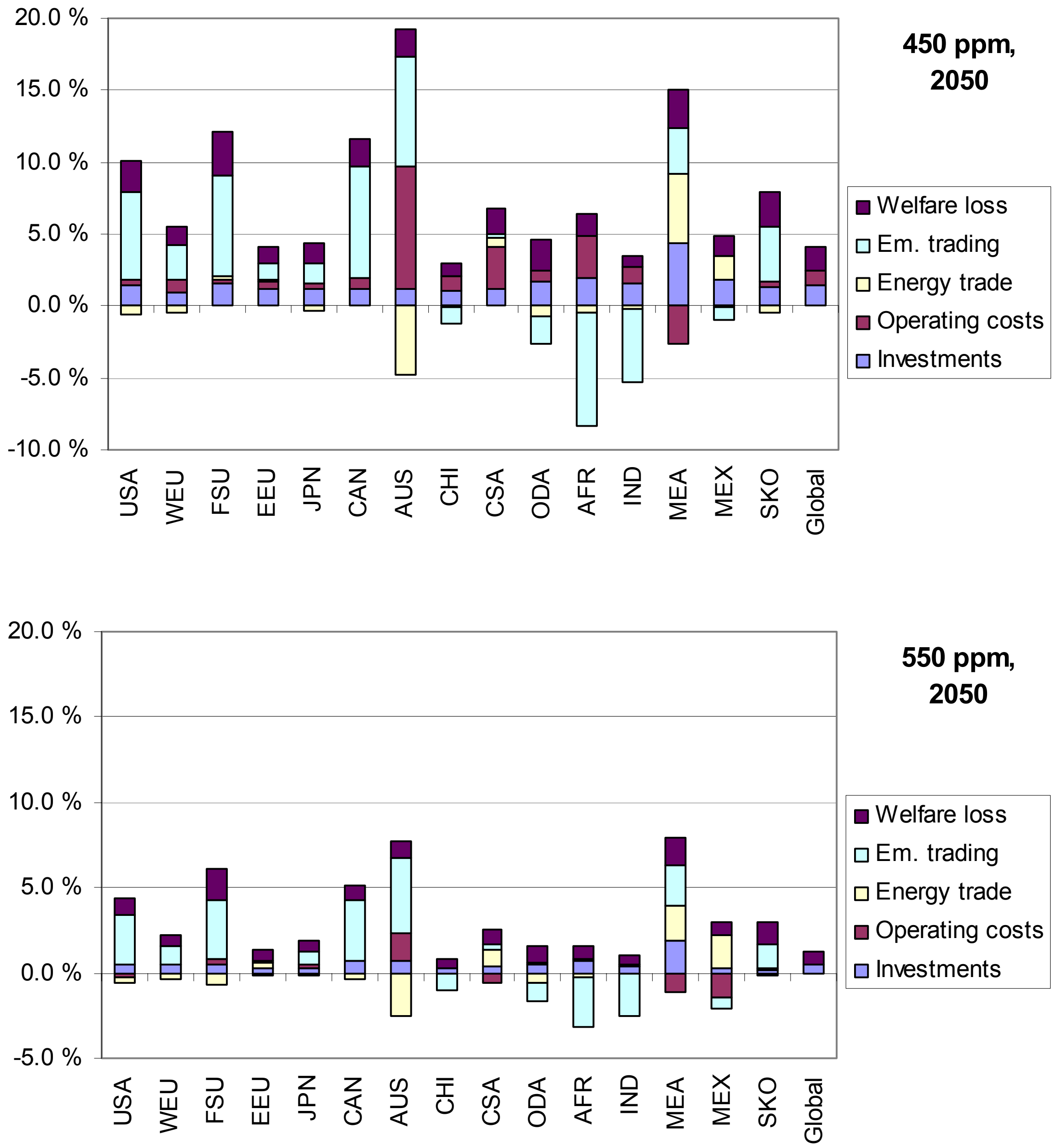


Figure 17. Breakdown of regional mitigation costs per GDP with the Triptych approach in TIMES in 2050 in the B2 TIMES scenarios with 450 ppm (left) and 550 ppm (right) reduction targets.

The cost breakdown in 2050, depicted in Figure 17, portrays a different view. As the emissions converge to the levels of 15,700 Mt CO_2-eq per year with the 450 ppm target and 27,300 Mt CO_2-eq per year with the 550 ppm target, the widening gap between the emission targets produces increasingly different results in terms of mitigation costs.

Welfare losses rise with tightening emission limits, with countries in the former Soviet Union (FSU) and the Middle East incurring the largest losses. Demand for international transportation is reduced most as it is fuelled solely by kerosene and heavy fuel oil and without any viable options for emission reductions. Therefore, in 2050, emissions account for roughly two-thirds of aviation energy costs with the 450 ppm target, substantially increasing the price of aviation from the baseline. Energy prices for aviation and navigation are, therefore, quite uniform in all regions in the reduction scenarios due to the common price of allowances. Last, as the baseline scenario projected lower prices for kerosene and fuel oil in the FSU and Middle East, the relative price increase for international transportation is higher in these regions, producing a larger response through demand-price elasticity and thus also a larger welfare loss.

With the 450 ppm target, a new important cost class is the O&M costs, as direct mitigation measures are taken most prominently in agriculture. The price curve of measures to extensively control rumination and rice CH_4 and crop, manure and fertilizer N_2O was assumed to rise steeply after the 10% – 30% reduction potential from the baseline, varying between different emissions. As already indicated in Figure 11, these measures are used to roughly mitigate 4000 Mt CO_2-eq of emissions in 2050. This raises the market prices of emission allowances considerably. It should be noted, however, that the actual price of the measures is very uncertain and this study uses a rough estimates of around 500 \$/t CO_2-eq as the last price step. The most costly options were not needed with the 550 ppm target, resulting in significantly lower overall and marginal costs.

The overall costs per GDP and the effect of different baseline scenarios with regard to mitigation costs is shown in Figure 18 and Figure 19. The A1 scenario with the highest economic growth clearly produces larger costs, and, vice versa, the low-growth A2 the lowest. With higher economic growth, the demand for energy grows, and as most of the mitigation options have limited capacities or applicabilities, more expensive measures have to be taken to satisfy the energy demand. This effect can be seen with most Annex I regions.

However, the demand growth is not directly behind the steep rise of mitigation costs in the Middle East. The majority of the costs in the Middle East can be attributed to trade losses, and as the oil price is also driven by the pace of economic growth in the baseline but not so much in the reduction scenarios, the loss of revenue is significantly larger in the A1 scenario with high growth. It should be noted, however, that the revenues from oil trade are increasing also in the reduction scenarios, but only with a slower pace.

As a result of emissions trading, most non-Annex I regions are able to profit from the emission reductions and have negative mitigation costs. These regions reduce their emissions more than the effort sharing scheme would require and sell the resulting excess allowances. Thus the sales profits are also dependent on the price of allowances, which is driven by the pace of economic growth.

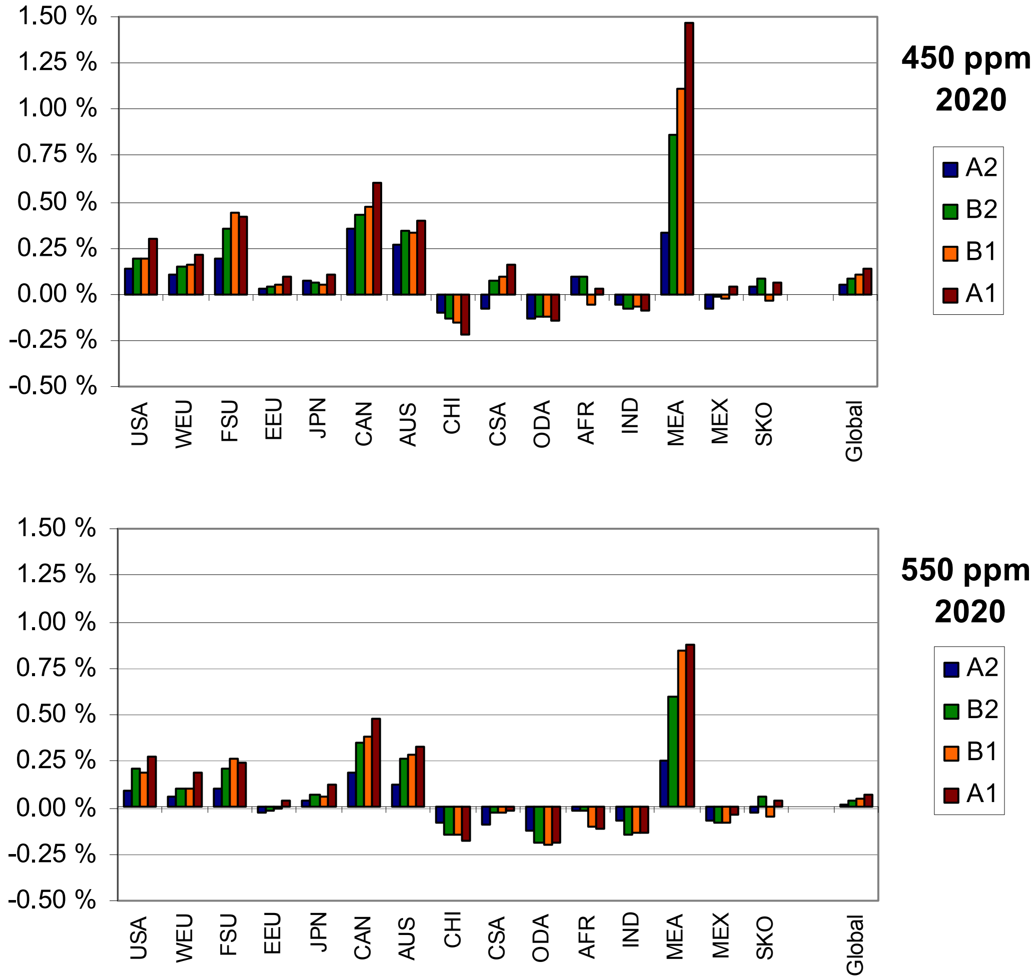


Figure 18. Regional mitigation costs per GDP with the Triptych approach in TIMES in 2020 with four baseline scenarios and 450 ppm (top) and 550 ppm (bottom) targets.

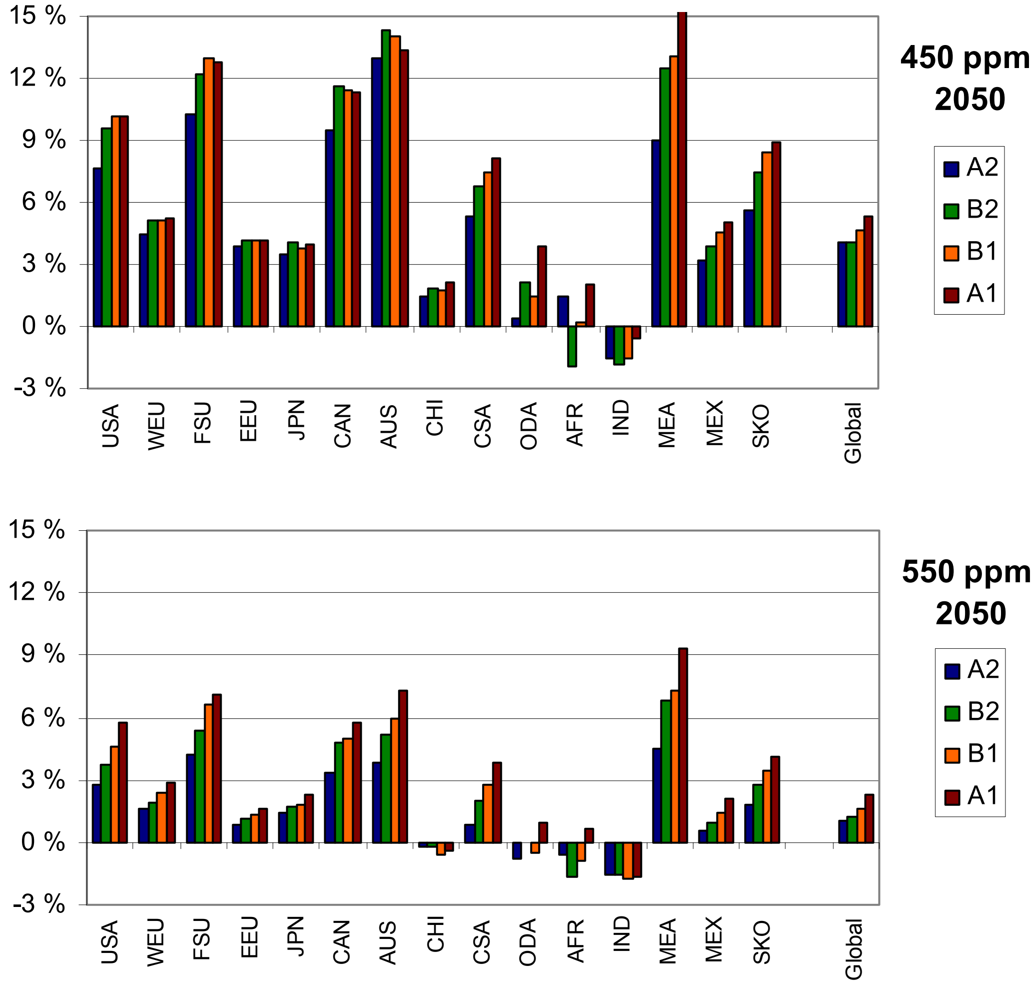


Figure 19. Regional mitigation costs per GDP with the Triptych approach in TIMES in 2050 with four baseline scenarios and 450 ppm (top) and 550 ppm (bottom) targets.

The effect of the emission limits on the prices of different energy forms is shown in Figure 20. The regional split of TIMES is further aggregated to eight regions in the figure in order to maintain readability. The increase in electricity prices was quite uniform across the regions, the greatest deviations being a greater increase in Australia and China, which both use mainly coal in their electricity production, and a much lower increase in Central and South America, which has large hydropower potential. It should be noted that the price increase estimates of the TIMES model are only system prices and that the model does not feature market prices and real-life market mechanisms. Therefore, these estimates should only be considered indicative.

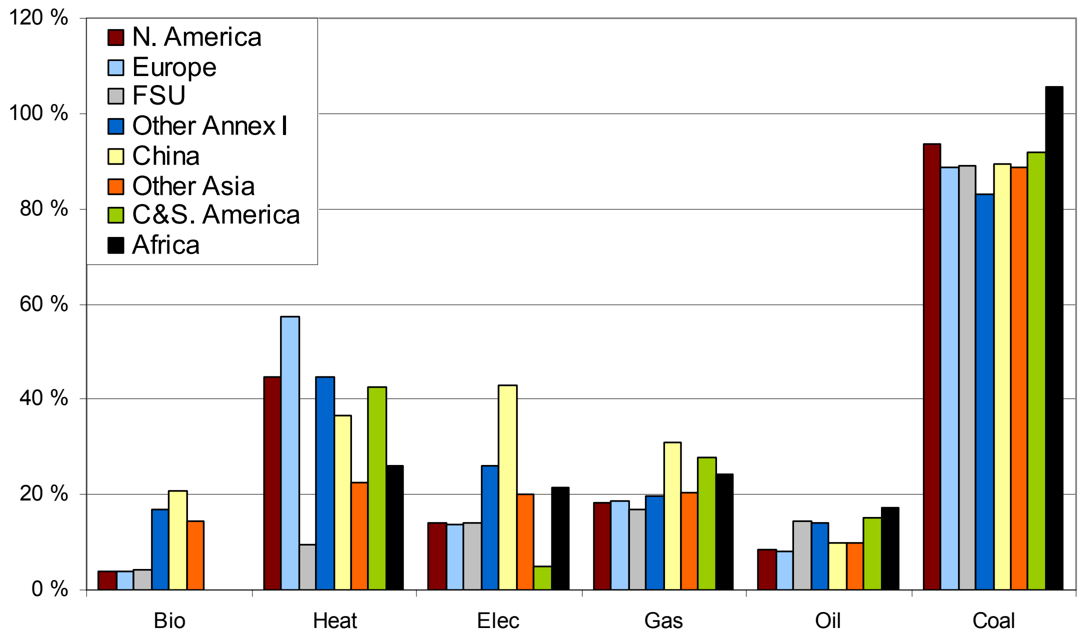


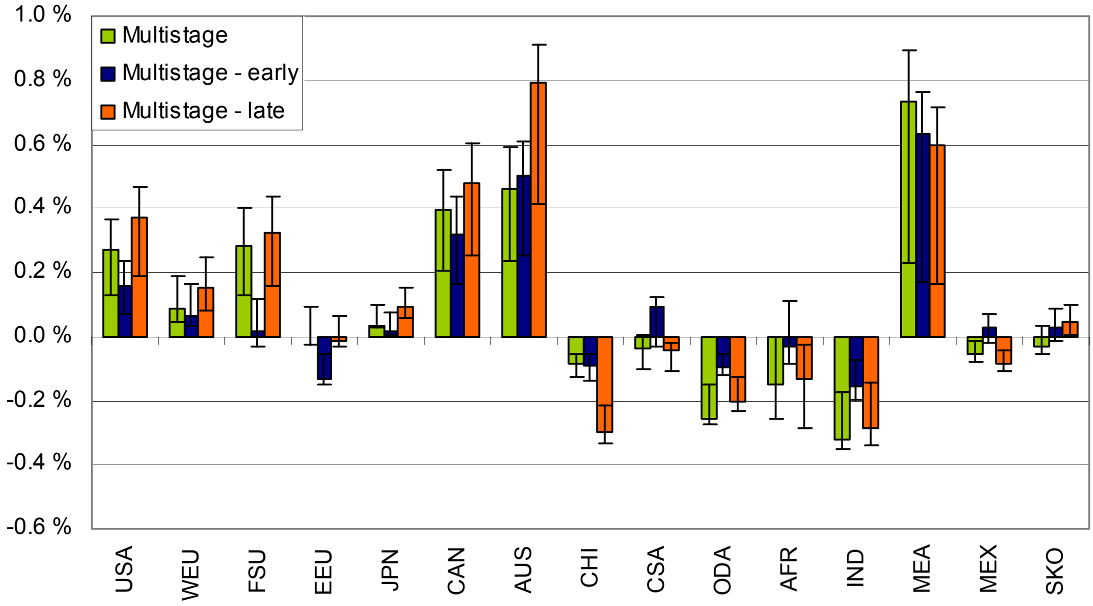
Figure 20. System price increase in TIMES from baseline for different energy forms with the 550 ppm target in 2020, including the price of emissions for fossil fuels.

5.3 Multistage effort sharing

As noted earlier, with our assumption of perfect allowance markets, effort sharing only affects a country's costs. Therefore, comparing the results from Multistage effort sharing to that of Triptych produces exactly the same scenarios, apart from the distribution of costs and profits from emission trading to the regions.

The Multistage effort sharing in this study was defined to have a 550 ppm target with GDP per capita as the regional threshold for participation. The resulting regional costs are shown in Figure 21. Comparing the figure with the Triptych 550 ppm case presented in Figure 18 and Figure 19, it can be seen that the Multistage effort sharing allocates more allowances to least developed regions, thus increasing India's and Africa's profits from emission trading and increasing the costs of other regions, including most other non-Annex I regions, such as China and Central and South America. From the equal cost per GDP point of view, this is thus a more inequitable approach than Triptych.

Figure 21 also includes a sensitivity analysis of early or late participation by the developing countries. Predictably, early participation increases the developing countries' mitigation costs and lowers the costs of industrialized countries, also vice versa with late participation. However, in 2020, most of the developing countries and, in 2050, Africa and India, still face negative costs, even with early participation. Also, with late participation, the costs are actually higher for most developing regions in 2050 compared to the main Multistage case. For developed regions, the cost levels are quite similar between all approaches.



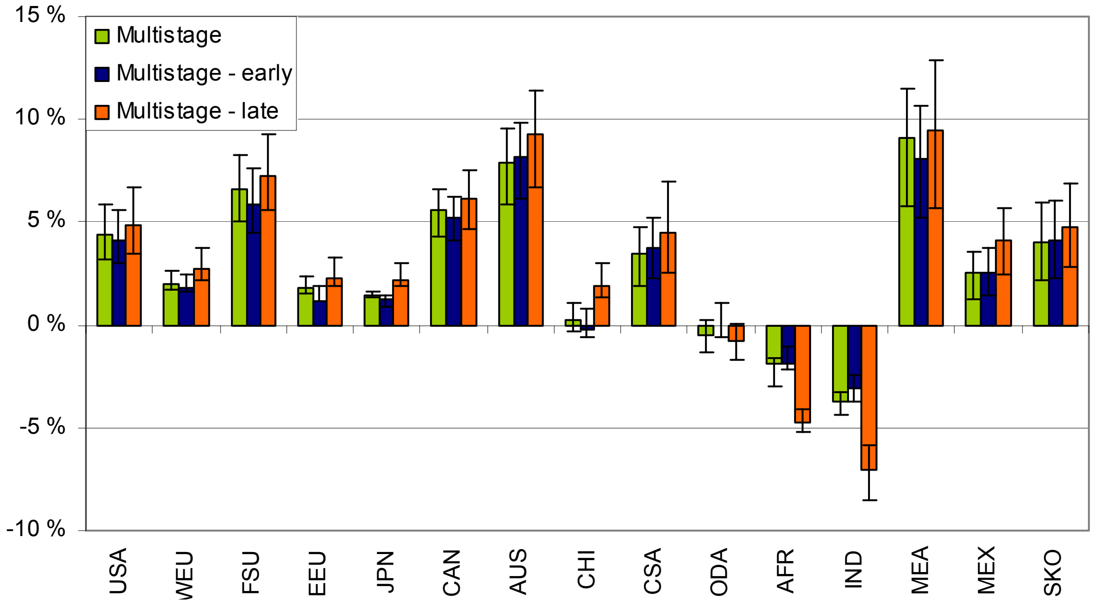


Figure 21. Regional mitigation costs per GDP from TIMES with Multistage effort sharing in 2020 (top) and 2050 (bottom) along with sensitivity analysis of early and late participation by the developing countries. The columns represent the median of the four different growth scenarios and the ranges the maximum and minimum values.

5.4 Equal costs approach

As the regional effort is measured through mitigation costs in this study, by using the efficient market hypothesis we can, in principle, calculate an initial allocation of emission allowances that would equalize the regions' mitigation costs relative to their baseline GDPs. This would produce an equitable effort according to the principle of comparable effort.

The equal cost effort sharing is based on the mitigation cost $C_{r,t,s}$ and emissions $M_{r,t,s}$ of region r from the TIMES model for a baseline scenario s and year t (excluding emissions trade in the mitigation cost), baseline GDP $Y_{r,t,s}$ of the region and the market price of emission allowances $p_{s.t}$ for the scenario and year. The equitable allocation $A_{r,t,s}$ would then be defined as

$$A_{r,t,s} = \left(\frac{C_{r,t,s}}{Y_{r,t,s}} - \frac{\sum_r C_{r,t,s}}{\sum_r Y_{r,t,s}} \right) p_{t,s}^{-1} + M_{r,t,s}$$

which is the cost per GDP of the region minus the global average cost per GDP, per the price of allowances, plus the actual emissions of the region. Therefore, the scheme would allocate allowances in excess of actual emissions to regions with higher than average relative mitigation costs and vice versa.

The evident practical shortcoming of this approach is its reliance on many variables: the baseline scenario, mitigation costs, emissions and allowance prices. As the initial allocation of allowances has to be done in advance, the effort sharing would heavily rely on uncertain forecasts, the most doubtful of which would inevitably be the volatile market price of allowances. Also, the model approach used only captures trade effects with energy and emission allowances, not with other commodities. In practice, it would also be hard to verify the actual mitigation costs as they are calculated as the difference to the baseline. Due to these uncertainties, we constrain our comparison of different emission allocations to the year 2020.

Figure 22 and Figure 23 compare regional emissions actually occurring in the cost-optimal solution of TIMES to the initial emission allocations according to Equal cost, Triptych and Multistage effort sharing schemes with the two emission targets. In order to depict the variability with regard to different economic growth levels, the columns represent the median from the four different SRES scenarios, while the ranges represent the highest and lowest values.

The figures capture the same trends that the cost figures presented previously have exhibited. Triptych and, especially, Multistage allocate a great excess of allowances for the developing world, much more than the Equal cost principle would justify according to the results from TIMES. Especially China, India, Southeast Asia and Mexico receive roughly one-third extra to the Equal cost allocation with Triptych, and with Multistage India receives yet more. It is also good to note that even with the Equal cost approach, most developing regions also receive allowances in excess of their emissions, thus being able to gain profit from emission trading.

Conversely, the Equal cost approach would allocate more allowances to the industrialized countries than is implied by Triptych or Multistage effort sharing, but mainly still slightly less than the countries emissions would require. The industrialized countries' strong GDP relative to the mitigation costs results in them being net buyers of allowances when costs per GDP are equalized.

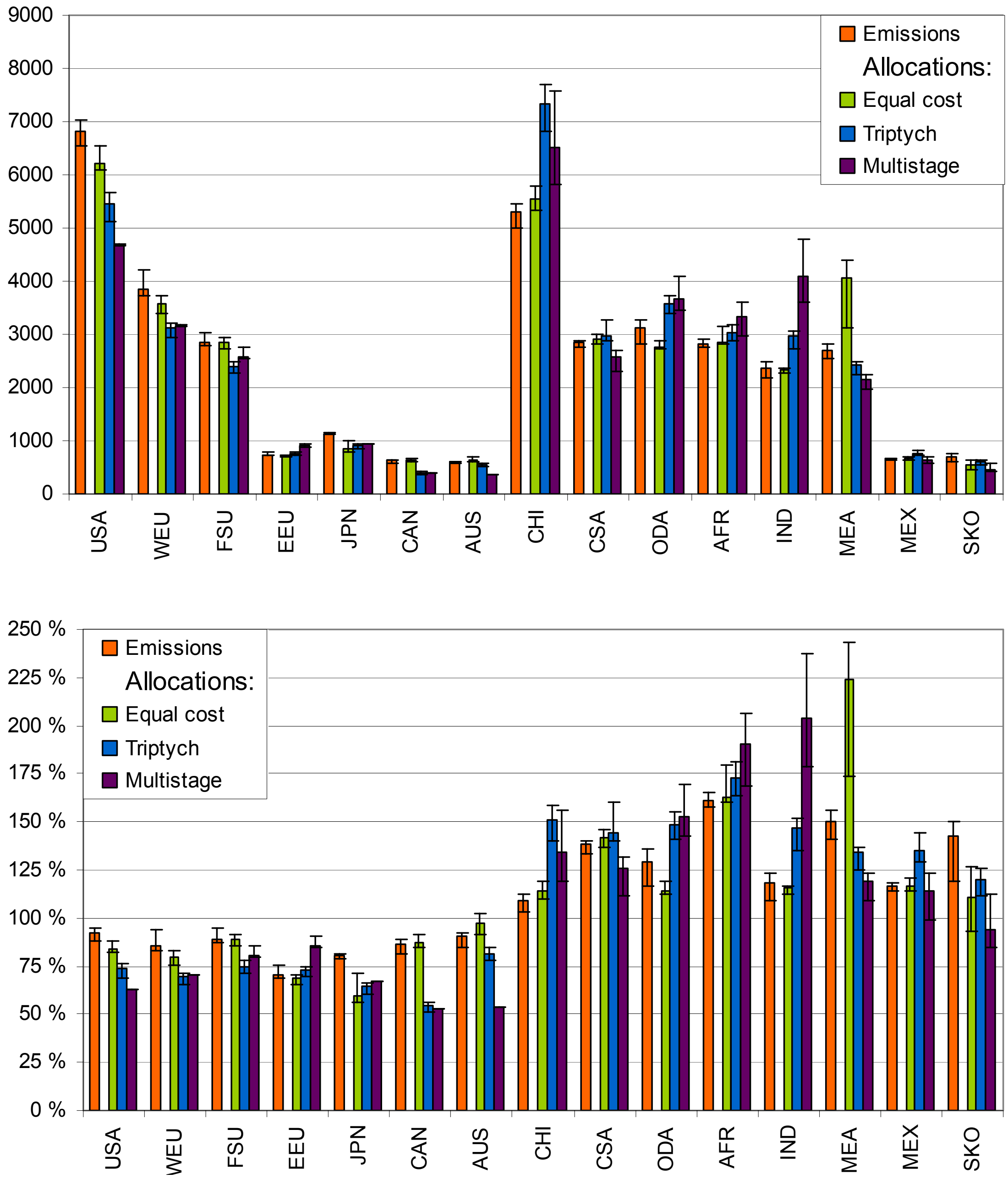


Figure 22. Comparison of actual 2020 emissions in the TIMES scenarios with the 450 ppm target and different initial allocations of emissions allowances in absolute terms (top, [Mt CO_2-eq]) and relative to 2000 emissions (bottom). The columns represent the median of the four different growth scenarios and the ranges the maximum and minimum values.

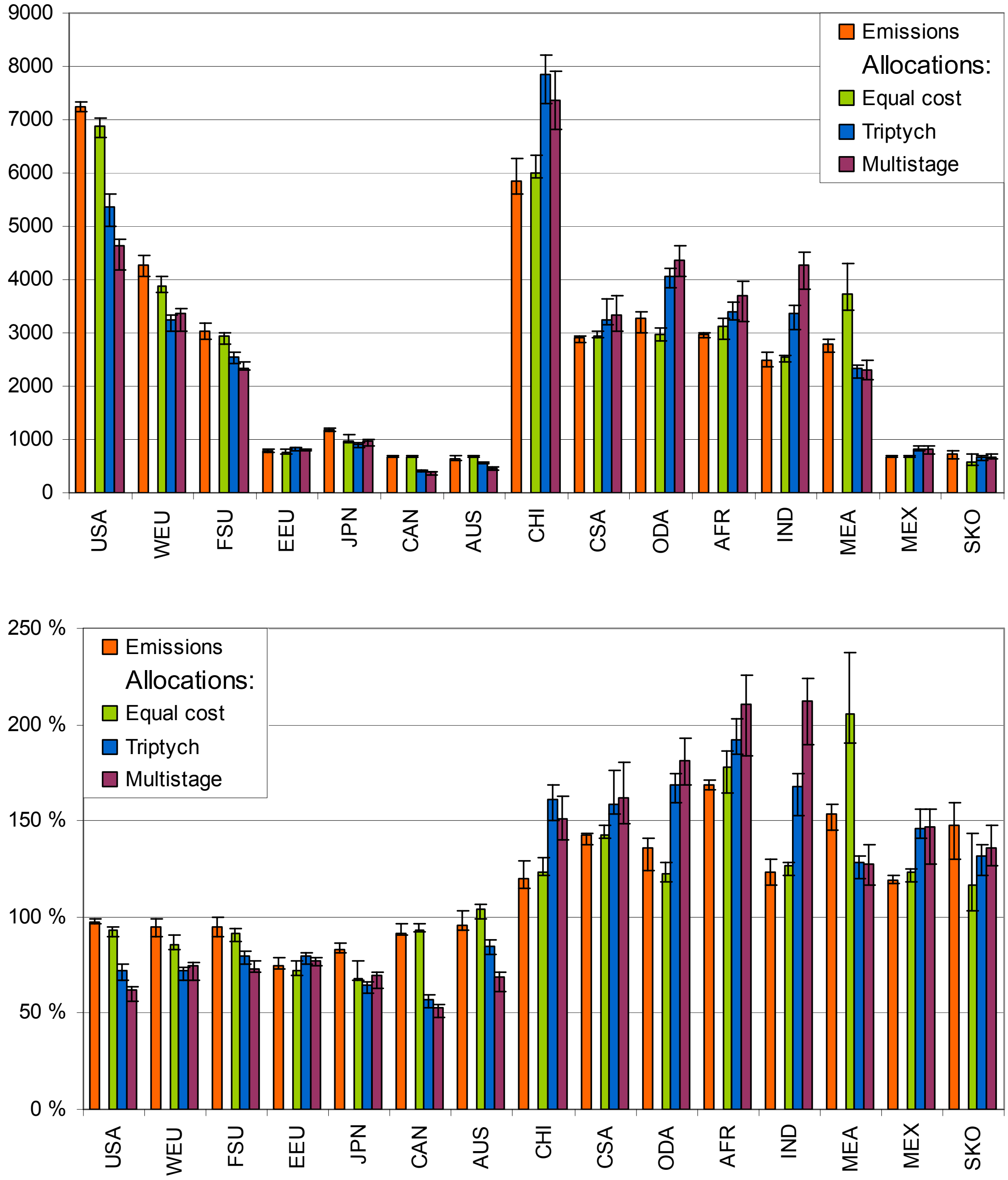


Figure 23. Comparison of actual 2020 emissions in the TIMES scenarios with the 550 ppm target and different initial allocations of emissions allowances in absolute terms (top, [Mt CO_2-eq]) and relative to 2000 emissions (bottom). The columns represent the median of the four different growth scenarios and the ranges the maximum and minimum values.

5.5 The effect of transaction costs

The introduction of transaction costs mainly affects mainly the regional costs and trade flows of allowances, presented in Figure 24 and Figure 25, as the direct effect deals with the amounts and prices traded on the allowance markets. It is also clear that the regions most involved with emission trading are likely to be affected more. This can be seen as a rise in mitigation costs for Canada, the USA and the FSU, and diminished returns especially for China and India in Figure 24. A larger increase in relative terms is seen in the global cost, which is more than doubled. Therefore, smooth operation of the allowance markets would be vital for reaching low overall mitigation costs.

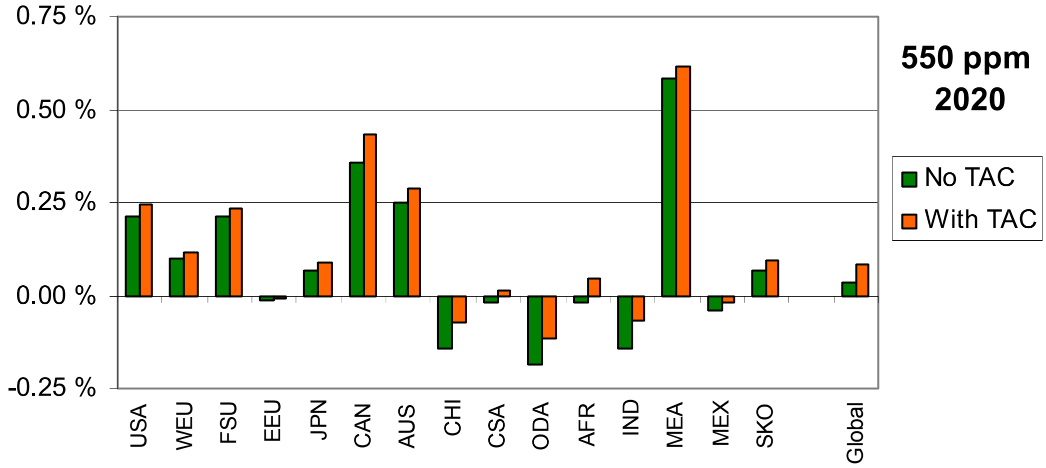


Figure 24. Regional mitigation costs per GDP from TIMES with Triptych 550 ppm effort sharing in 2020 with and without transaction costs (TACs) in emissions trading.

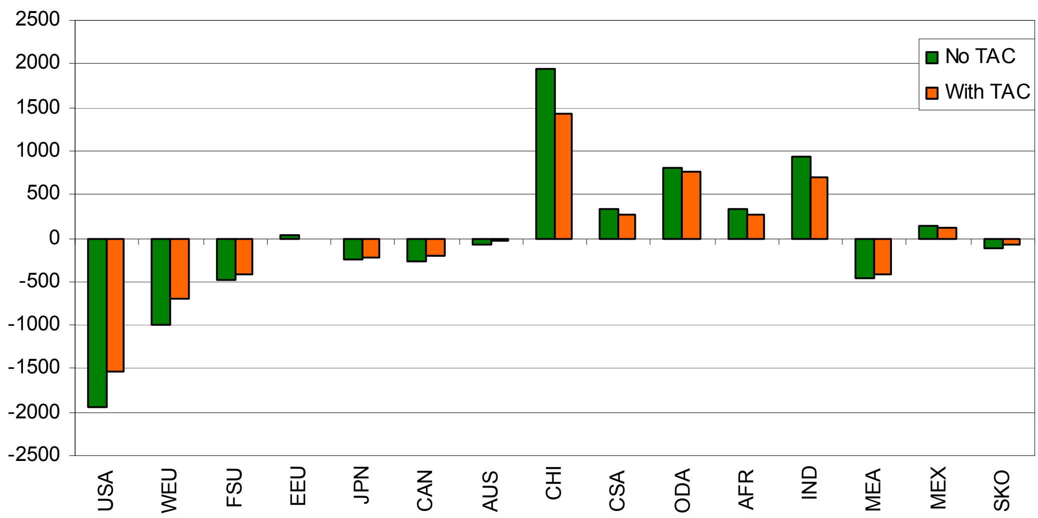


Figure 25. Emission net sales [Mt CO_2-eq] from TIMES with Triptych 550 ppm effort sharing in 2020 with and without transaction costs (TACs) in emissions trading.

5.6 Constraining allowance trading

In the constrained trading scenario, a large net seller was assumed to withhold its allowances. China was chosen for illustrative purposes only in this case study as it was the largest net seller of emissions in the normal reduction scenarios. It is also a large country holding slightly over 20% of all allowances with the Triptych allocation and might also hold relevant market power in practice.

The main results from the market power case are presented in Figure 26 and Figure 27. The cost distribution changes slightly from the normal case as the growing scarcity of allowances raises its price roughly by one-third, from 15 \$/t to 21 \$/t. In China, however, there is an excess of allowances resulting in a zero allowance price and a slight increase in emissions from the baseline. The latter effect is due to a decreased global market price and increased consumption of fossil fuels in China. Overall, the country refusing to trade loses its revenues from emissions trading but might gain slightly on energy prices. Even though the total cost is slightly less than in the baseline, it is higher than in the case where China is selling its allowances. Therefore, as trade theory suggests, a country cannot gain financially by restricting its allowance trading.

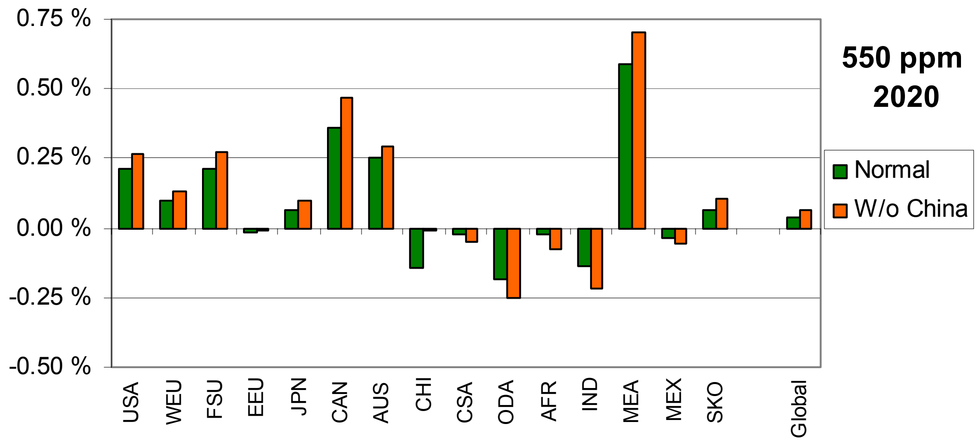


Figure 26. Regional mitigation costs per GDP from TIMES with Triptych 550 ppm effort sharing in 2020 with China selling or not selling emission allowances.

However, if we look at the changes in the system prices of energy in China in Figure 27 and compare them to Figure 20, we can find evident justification of why a country might restrict its trading. China faced some 40% increase in electricity and 90% increase in coal use prices when engaged with the global allowance markets in 2020. Coal and electricity make up over half of China's total final energy consumption in the baseline and over 80% in industry. Therefore, major political pressure might emerge against participating in the emissions trade if residents and companies were faced with steep increases in energy prices and were not compensated with the revenues gained from exporting the allowances. Solutions to this dilemma might include using some of the emission trade revenues to subsidize clean energy production or consumption. A better solution might be a fragmented initial distribution of allowances to different actors in the allowance market.

India and Africa, the two other important net sellers in our scenarios, only hold around 8% of total allowances each, and sell allowances with only half the amount for China and face more modest price increases. Even so, the situation is similar with them and all other net sellers of allowances.

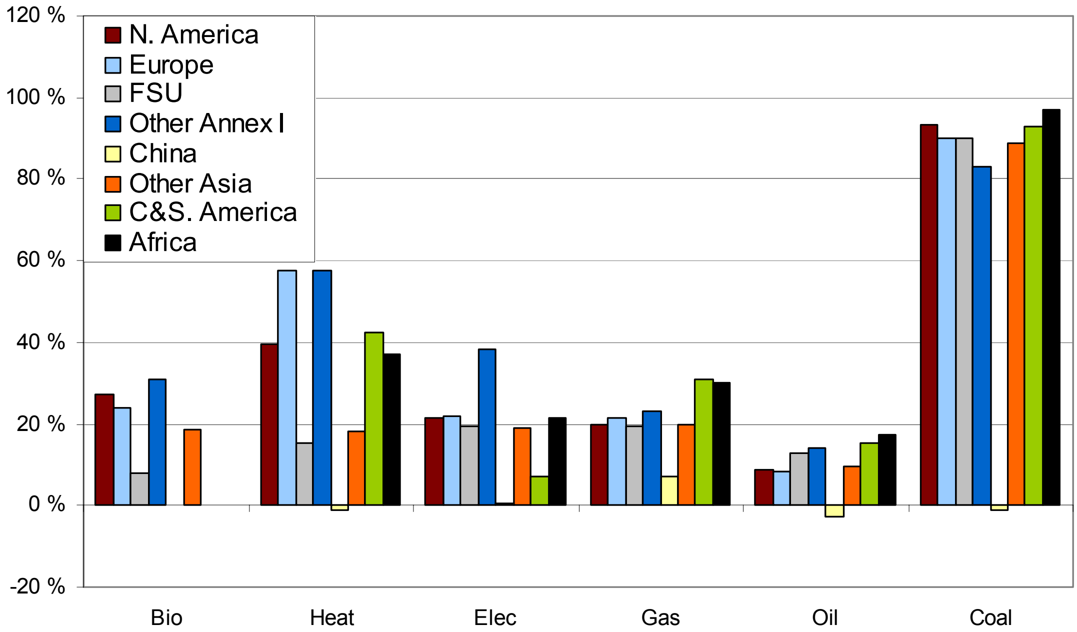


Figure 27. System price increase in TIMES from the baseline for different energy forms with the 550 ppm target in 2020, including the price of emissions for fossil fuels in the case where one region, China in this case, decides not to sell allowances.

5.7 Effects on Finland

VTT conducted a scenario study on the effects of the unilateral emission reductions of the European Union (Ekholm et al. 2008), which also assessed the effects on Finland in detail. From the viewpoint of Finland, the scenario setup is, in principle, exactly the same in both studies. As a small country, the actions of Finland do not have an impact on the price of emissions allowances on the global market; therefore, Finland acts as a price taker. Due to this reasoning, the actions of Finland can be assessed separately from the global scenarios. As already stated, in perfect emissions allowance markets, the mitigation effort carried out by a country only depends on the price of the allowances, not on the amount of emissions allocated to the country. Therefore, we can also separate the actual mitigation actions in Finland, which are defined by the prevailing market price, from the assessment of effort sharing with different initial emission allocations for Finland.

The Finnish GDP in the baseline was assumed to be 212 billion US$ (2000) in 2020 and total GHG emissions 83 Mt CO_2-eq. The median reductions from 1990 emissions in 450 ppm Triptych, 550 ppm Triptych and 550 ppm Multistage for Finland were 24%, 20.5% and 21.2% respectively. By scaling the allowances as was done for the global model, the reduction targets resulted in allowances between 51.4 Mt CO_2-eq (Triptych 450 ppm, A1) and 59.6 Mt CO_2-eq (Triptych 550 ppm, A2). The initial allocation is presented in Figure 28.

Using the market prices from the global model for 2020 with the 450 ppm and 550 ppm targets and four growth scenarios, we interpolated the Finnish emissions calculated with the Finnish TIMES model as reported in (Ekholm et al. 2008), thus producing the Finnish mitigation efforts relating to the global scenarios. The results indicated annual emissions of 69 Mt CO_2-eq with a 20 €/t price level and 62 Mt CO_2-eq with a 50 €/t price level. The purchase of allowances would then produce costs between 145 M$(2000) and 433 M$(2000), which would equate with 0.07% to 0.20% of baseline GDP, 0.12% on average. This is only slightly higher than the Western European average of 0.11%. Combined with the energy system costs, the total cost would range from 250 M$(2000) to 710 M$(2000) or 0.12% to 0.33% of 2020 GDP, which is clearly higher than the Western European costs, which were between 0.05% and 0.19% of GDP in 2020.

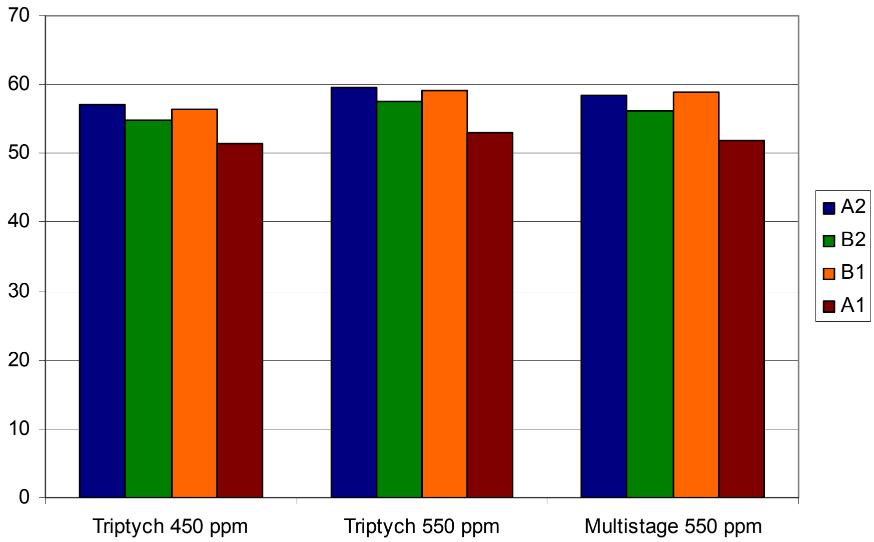


Figure 28. Finnish initial emission allowances [Mt CO_2-eq] in 2020 with three different effort sharing schemes and four growth scenarios.

6. Recalibrating EVOC based on TIMES results

Comparing the development of global emissions between TIMES and EVOC in Figure 29 reveals that the models assume quite different sectoral mitigation potentials, especially in the 550 ppm case. The results from TIMES would indicate early mitigation in electricity generation and late mitigation, if at all, in agriculture. The domestic & waste sector, including residential, commercial, waste and transportation emissions, and industry behave quite similarly in the models. However, the global figures do not exhibit some important regional differences.

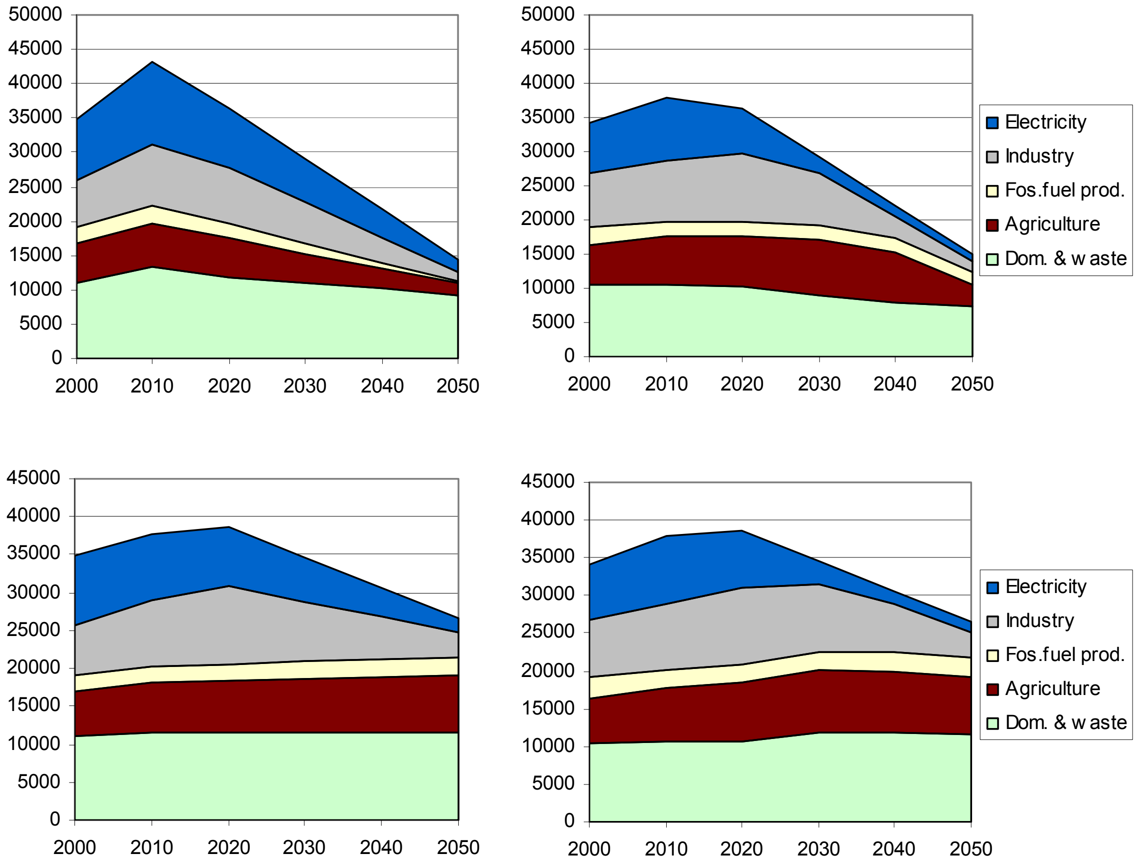


Figure 29. The development of global emissions [Mt CO_2-eq] with 450 ppm (top) and 550 ppm (bottom) targets according to EVOC (left) and TIMES (right).

Due to differing sectoral shares between the emissions for different regions, the assumptions for sectoral mitigation potential is likely have an effect on the allocation of emission allowances. A regional breakdown of emissions in 2020 and 2050 with both concentration targets is shown in Figure 30 and Figure 31. In 2020 the differences between EVOC and TIMES results are minor, most notable being industrial and electricity emissions in China and the level of agricultural emissions.

The results for 2050, however, differ considerably on the regional level with both reduction targets. Agricultural emissions in the EVOC results decrease to extremely low levels in all regions except Africa. The difference between the model results is larger with the 550 ppm target as the higher emissions limit does not force TIMES to carry out the expensive agricultural non-CO_2 mitigation options. Also, electricity and industrial emissions for non-Annex I regions are considerably higher with the 550 ppm target in 2050.

The most distinctive difference with both targets in 2050 is, however, the domestic and waste sector. In non-Annex I regions the domestic emissions are allowed to grow or stay on the same level as in 2020, whereas in Annex I regions the emissions are bound to decrease to a quarter of the 2020 levels. The domestic sector emissions are slightly ambiguous with the sector classification used in EVOC; therefore, the finer grained breakdown of TIMES should be examined to interpret the differences.

As presented in Figure A1 and Figure A2, transportation emissions account for roughly two-thirds of the domestic sector emissions (including agriculture, transportation, commercial and residential sectors) in 2020 and over 80% in 2050 in Annex I regions with both reduction targets, and over half in 2020 and two-thirds in 2050 in non-Annex I regions. The reduction efforts in the transportation sector in the TIMES results include hydrogen and natural gas for road transportation, reducing the emissions from vehicles to very low levels. The rest of transportation emissions are mostly made up by aviation and maritime, which have no reasonable mitigation options other than reduced consumption, which is also occurring in the TIMES results due to the rising allowance prices.

The regions facing most disparate emissions in 2050 in the two models are the USA, Canada and Australia, for whom only 30% – 40% of the TIMES emissions are allocated by EVOC. As a result, both regions have also very high relative mitigation costs due to the need to buy large amounts of allowances, as indicated by Figure 17 and Figure 19. Also, the FSU lacks half of its allowances, but the higher emissions-to-GDP ratio raises its relative mitigation costs above the others. Western Europe only receives a slightly higher share of the allowances it needs in the initial allocation.

Based on these observations, the Triptych approach in the EVOC model was recalibrated with the 550 ppm target to accord with the reduction potential assumptions in the TIMES model. Even though comparing Figure 32, which shows the sectoral 550 ppm emission profile with recalibrated EVOC, to Figure 29 does exhibit a quite similar picture before and after the recalibration, there are large differences in the emissions allocations that different countries receive.

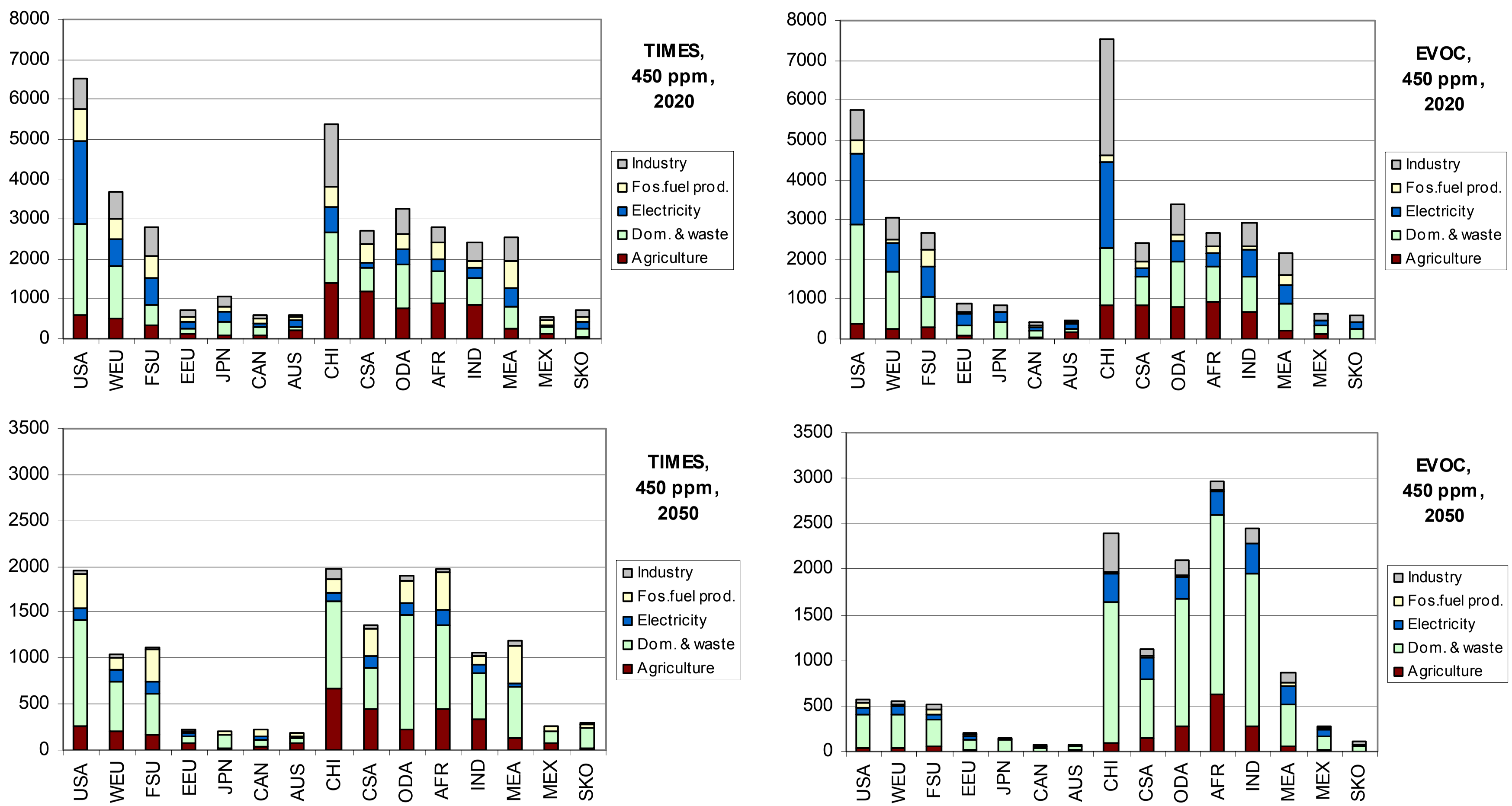


Figure 30. Regional emissions [Mt CO_2-eq] with the 450 ppm target in 2020 and 2050 according to TIMES and EVOC.

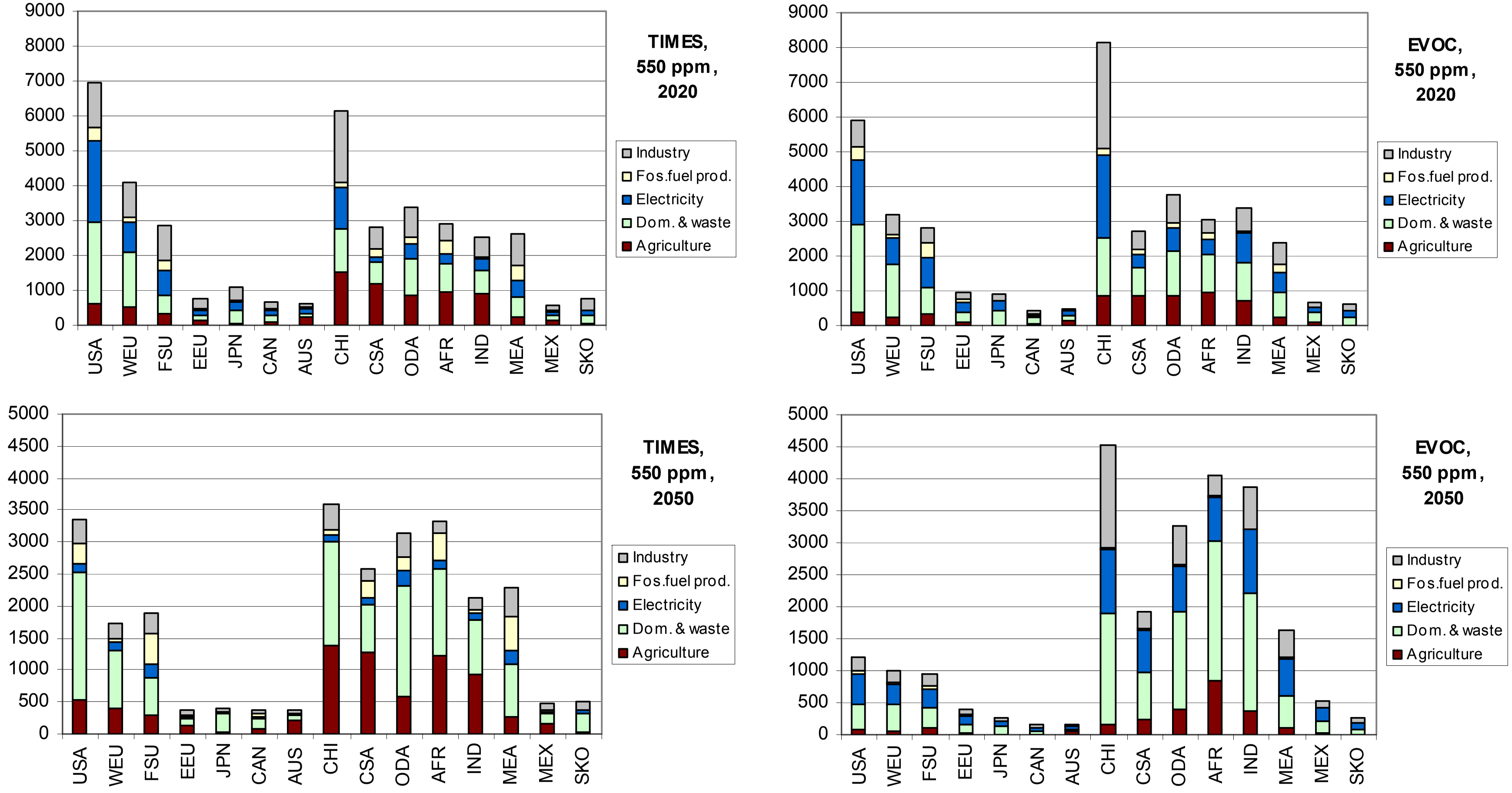


Figure 31. Regional emissions [Mt CO_2-eq] with the 550 ppm target in 2020 and 2050 according to TIMES and EVOC.

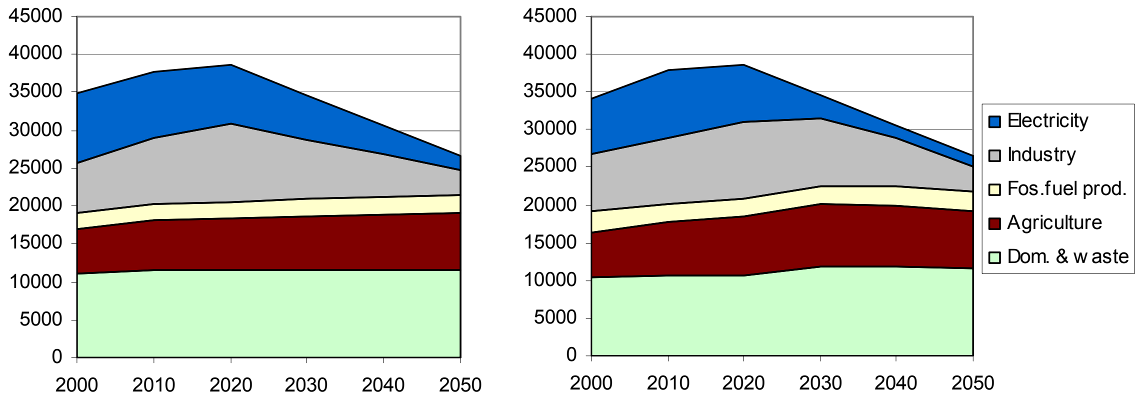


Figure 32. The development of global emissions [Mt CO_2-eq] with 550 ppm target according to recalibrated Triptych from EVOC (left) and TIMES (right).

The emission allocations with the 550 ppm target before and after Triptych recalibration are compared in Figure 33, and as we can see, the differences are small in 2020 but considerable in 2050. When interpreting the figure it is critical to note the logarithmic scale, which understates the differences but allows the presentation of both small and large allocations in the same figure. For most Annex I countries the difference between the results before and after the calibration is over 10%. But e.g. for Australia the allowances in 2050 are 66% larger after the recalibration. For non-Annex I countries the standard deviation for allowances before and after recalibration is 27%.

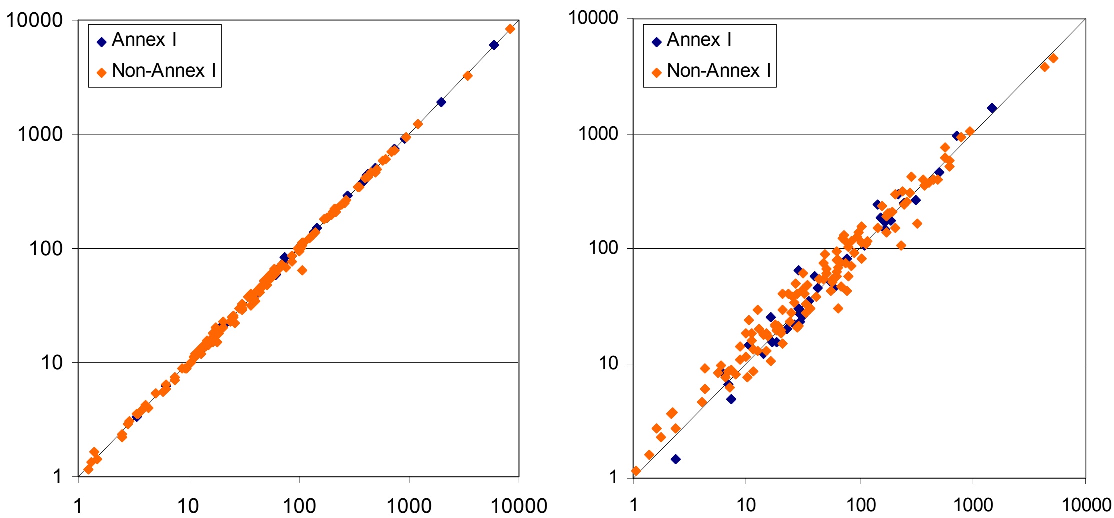


Figure 33. Emission allowances [Mt CO_2-eq] in 2020 (left) and 2050 (right) with the 550 ppm target using the original (X-axis) and recalibrated (Y-axis) Triptych approach. Note the logarithmic scale, which visually understates the differences.

Although some of the differences cancel out when countries are aggregated to the geographical regions used in TIMES, there are still noticeable differences in the mitigation costs due to the Triptych recalibration. Figure 34 compares the median costs per GDP before and after the recalibration. To some extent in 2020, and especially in 2050, the largest relative costs are considerably reduced and the excessive profits of some regions are decreased. Altogether, the allocation in 2050 after the recalibration can be seen as more equitable, thus underlining the importance of the background assumptions on which the effort sharing is based.

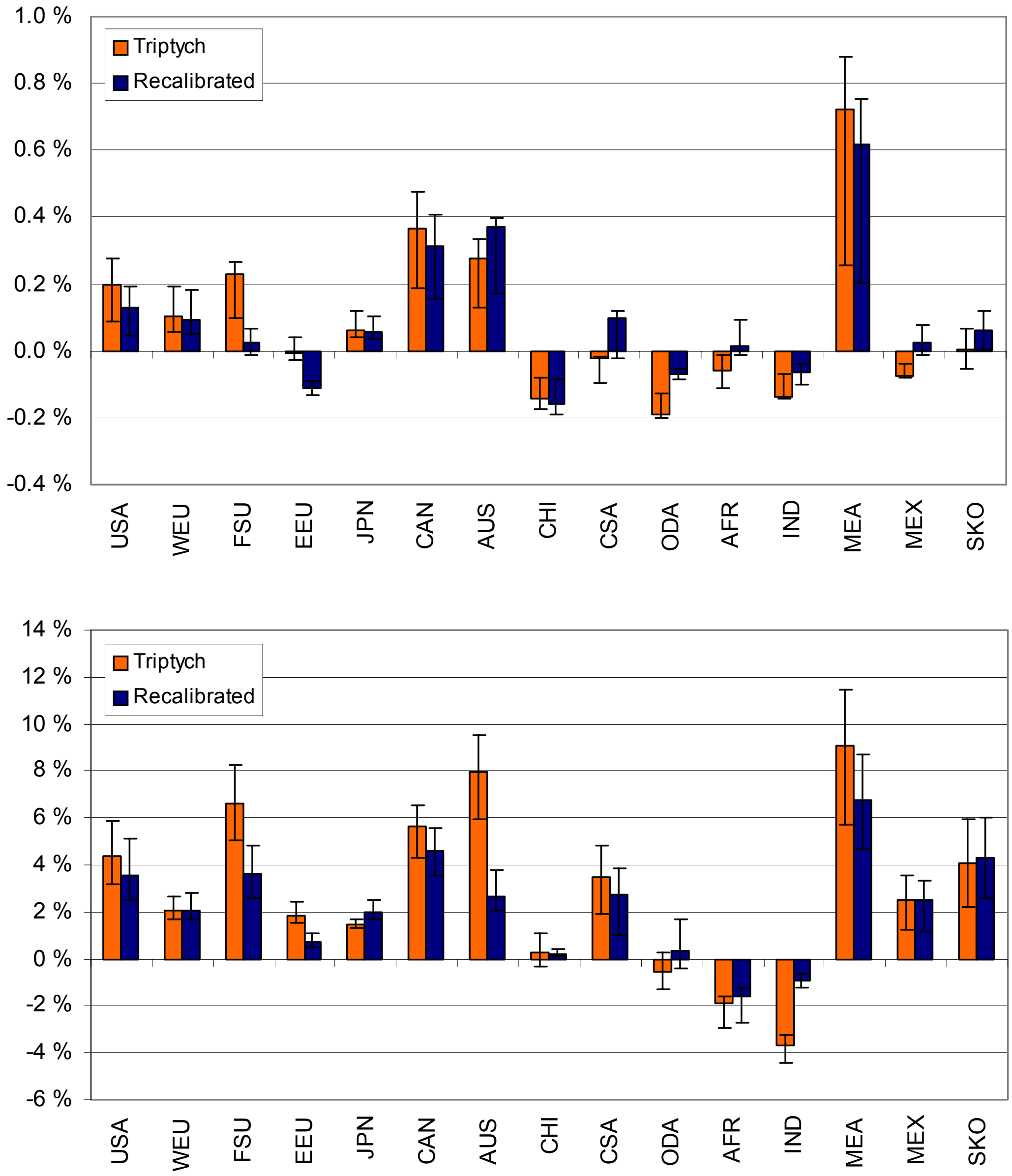


Figure 34. Regional mitigation costs per GDP in 2020 with Triptych 550 ppm effort sharing in 2020 (top) and 2050 (bottom) with the original and recalibrated Triptych approaches.

7. Conclusions and discussion

This study has analyzed global effort sharing of emission reductions in long-term scenarios using two models, the EVOC tool of Ecofys GmbH for calculating Triptych and Multistage emission allocations and ETSAP-TIAM, a global energy system model of the TIMES family for creating the scenarios. The analyzed scenarios included two emission limits with concentration targets of 450 ppm and 550 ppm and four economic and population growth projections, corresponding to the SRES scenario implementation of the IMAGE modelling team.

The cost-optimal mitigation strategy implied by the TIMES model showed that the greatest emission reductions would come from the energy sector and industry due to the phasing out of fossil fuels. The electricity sector would switch from coal to biomass, wind energy, new types of fission reactors, and, further in the future, also to fusion. Natural gas and coal could also be used in conjunction with carbon capture. Together, this technology shift would reduce the emissions from the electricity sector to almost zero, also reducing the emissions from upstream energy production as fossil fuel consumption is decreased. In industry, coal could be partially replaced by electrification and biofuels, also combined with CCS. Process emissions in clinker could be reduced through blended cements and carbon capture.

Other sectors would find it hard to reduce emissions to levels as low as in electricity generation, even though large mitigation potential still exists. In the transportation sector, road vehicles could switch to hydrogen, electricity and natural gas, while aviation and maritime show little mitigation options and are, therefore, faced with reduced end-use. Still, international transportation was the most important single emissions source by 2050. The inexpensive mitigation potential for agricultural emissions was assumed to be limited, around 15%. However, more expensive potential in fertilizer N_2O and rumination CH_4 was assumed to be used with the 450 ppm target in 2050 as the tightening emissions limit would raise the price of emission allowances to sufficiently high levels. However, these changes might also require a switch from rice to other cereals and from cattle to pork and poultry.

Generally, reduction measures were first taken in centralized processes, such as electricity production and industry. In these sectors there are usually more options for producing the desired product with lower emissions, for example using alternative fuels or CCS. In decentralized energy end-use processes such as transportation, the alternatives are often more scarce and expensive. In practice, it is also much easier to measure, verify and control emissions from large centralized processes compared to dispersed emission sources, such as agriculture and transportation.

Globally, the mitigation costs exhibited a direct relationship to the assumed pace of economic growth as more expensive mitigation efforts have to be carried out with higher economic growth and thus energy demand. The modelling principle is based on the principle of satisfying the energy demand projected in the baseline, having limited price-demand elasticity. The costs in 2020 were between 0.01% and 0.07% of the global GDP with the 550 ppm target and between 0.05% and 0.13% with the 450 ppm target, depending on the assumptions on economic growth, and respectively between 1% – 2.2% and 4% – 5.3% in 2050. The relatively low costs in 2020 and a steep rise thereafter result from the gradual tightening of the emissions targets: the emissions were allowed to grow to +30% and +20% from the 1990 levels in 2020 and shrink to –10% and –50% in 2050 respectively for the 550 ppm and 450 ppm concentration targets. If deeper emission reductions were conducted in 2020, the costs in 2050 would be more moderate.

The costs can be compared most easily to those reported in (Syri et al. 2008), where the same TIMES model is used to assess reaching the 2°C mean temperature target set by the European Union. The studies mainly differ with regard to the emissions profile and inclusion of afforestation options. First, in Syri et al. (2008), no strict emission limits are given, only a limit that the mean temperature change, calculated by the climate module of TIMES, should remain below 2 °C until 2100. This results in similar CO_2 emissions in 2050 to that reported by the IPCC with the 450 ppm target (IPCC 2007a), and, therefore, similar to the assumptions in EVOC. However, non-CO_2 emissions are not reduced in relative amounts compared to CO_2 in (Syri et al. 2008), a result reported also in this publication, leading thus to considerably higher CO_2-equivalent emissions. The overall greenhouse gas emissions amount to around 31 Gt CO_2-eq in 2050 in (Syri et al. 2008) and 20 Gt CO_2-eq by 2100, whereas a substantially lower target of around 16 Gt CO_2-eq in 2050 was used in this publication. As a direct consequence of the lower emission target, non-CO_2 emissions have to be reduced more and thus the mitigation costs rise considerably in the scenarios reported here.

Second, afforestation options were not included in the available mitigation measures in this study. In the scenarios of (Syri et al. 2008), afforestation accounts for roughly one-sixth of the emission reductions from the baseline in 2050. Without measures of this importance available, considerably more expensive measures have to be taken, thus raising the costs. The total mitigation costs in (Syri et al. 2008) amounted to 0.4% of global GDP, a significantly lower figure than in this study for the 450 ppm target and around the same with the 550 ppm target.

The regional mitigation costs, measured as the change in energy system costs from the baseline to the reduction scenario, were more influenced by emission trading, welfare losses and, in some regions, also by energy trade than actual investment or operation costs. Therefore, the costs were very different from the global overall cost in many regions, mostly above average in Annex I regions and below average or negative in most non-Annex I regions.

An important source of regional costs was the trade in emission allowances. However, this is also a weak point of the results as the market prices and trade flows are less robust for changes in the assumptions than the results concerning energy production and use. As the trade costs and revenues result from trade flows and prices, trade costs are a second order result and thus more uncertain and prone to errors. In real life, trade is also affected by varying transportation and transaction costs, exchange rates, regulation, taxes or subsidies and even speculation, which are hard to forecast, quantify and include in the model. Also, commodity trading was not included in the model, which would serve as a new source of costs or revenues. However, the results regarding regional costs can be thought of as indicative rather than exact, providing a way to analyze possible, not necessarily probable, futures.

The Middle East faced the greatest relative costs, mostly due to smaller trade revenues from oil as a result of lower demand for oil and thus also a lower market price. However, as the Middle Eastern oil trade revenues are increasing over time regardless of the emission reductions, it might be debatable whether the loss of revenues is a real mitigation cost or not. For Annex I countries, the USA, FSU, Canada and Australia also face higher costs, mostly from emission trading. A large share of the agricultural emissions in Australia increased its costs significantly in 2050 with the 450 ppm target as it was forced to reduce its agricultural CH_4 and N_2O emissions. Developing Asian countries and Africa, most notably China in 2020 and India in 2050, were able to sell considerable amounts of allowances, resulting in negative costs. The greatest beneficiary in 2050 was India, which received around 5% of its GDP as revenue from emissions trading and 2% of its GDP as overall profit from the effort sharing scheme.

Based on the TIMES results, an effort sharing scheme that would equalize the mitigation costs of different regions was considered. The calculation took the mitigation costs without emissions trading for each region and the market price for emission allowances, and compensated regions with greater costs with a surplus of allowances compared to their actual emissions as indicated by the results, and vice versa. The resulting effort sharing scheme, presented in Figure 22 and Figure 23, allocated more emissions to the Middle East, Canada, Australia, USA and Western Europe when compared to Triptych, less for developing Asia and Mexico, and relatively similar amounts to other regions.

One of the aims of Triptych and Multistage effort sharing is that developing countries should be given some leeway for economic growth. This aspect is satisfied according to our results as most developing countries face negative or small mitigation costs due to their ability carry out inexpensive mitigation efforts and sell the resulting excess to the industrialized countries. Therefore, this excess, compared to the equal cost allocation, can be thought as a sort of development aid, the amount of which is, of course, debatable. What is against the aim is that, according to the results, the effort sharing schemes benefit more the rapidly developing countries than the least developed countries. Therefore, Africa, for example, the least developed region, would benefit much less than China or other developing Asian countries in 2020.

Two special scenarios were used to study imperfect allowance markets. The effect of transaction costs and constraints in the market both showed the importance of market efficiency, and both imperfections resulted in roughly doubling global mitigation costs in 2020, as indicated by Figure 24 and Figure 26. The market constraint scenario, where a large net seller of allowances was assumed to refuse to sell, also showed that even though a country cannot financially benefit from constraining emissions trading, it might do so in order to maintain energy price stability as withholding the allowances negated the steep price increases in electricity and coal use. Besides raising the overall mitigation cost, the market imperfections might also have importance on the conceptual level. If the parties face constraints or costs for trading their allowances, the efficiency of a cap-and-trade system might fail and it might be not possible to separate efficiency and equity in the effort sharing.

A comparison of emission reduction potential estimates between EVOC and TIMES revealed noticeable differences, which are inevitably reflected in the emissions allocations and thus mitigation costs that the regions face. A recalibration of Triptych in the EVOC model resulted in notable differences in the effort sharing, and also created a more equitable emission allocation in the TIMES scenarios. This result underlines the importance of reliable assumptions of the reduction potentials used in the effort sharing procedure. What is also critical to note is that the supply curves of mitigation potentials in the future years entered into the ETSAP-TIAM model are by no means exact or certain. Therefore, the analysis also underlines the enormous challenge in fixing uncertain effort levels using partly unknown reduction measures into the distant future. A future agreement thus has to establish the parties' commitment to the global mitigation effort, but it also might be beneficial to leave some options open for readjusting the effort levels in the future if needed.

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Appendix A: Detailed breakdown of emissions

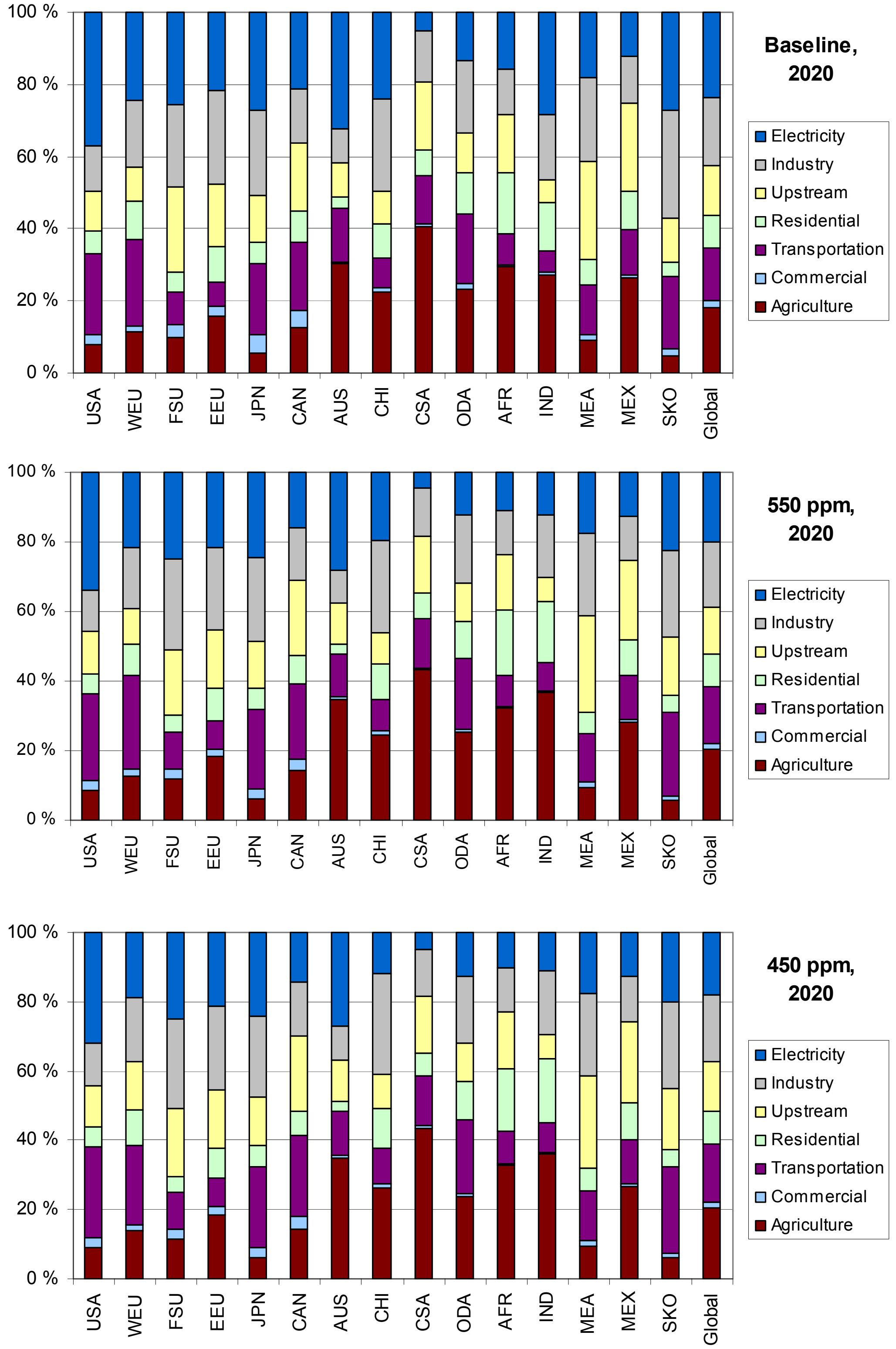

Figure A1. Regional and sectoral breakdown of regional GHG emissions in the 450 ppm (top) and 550 ppm (bottom) reduction scenarios in 2020.

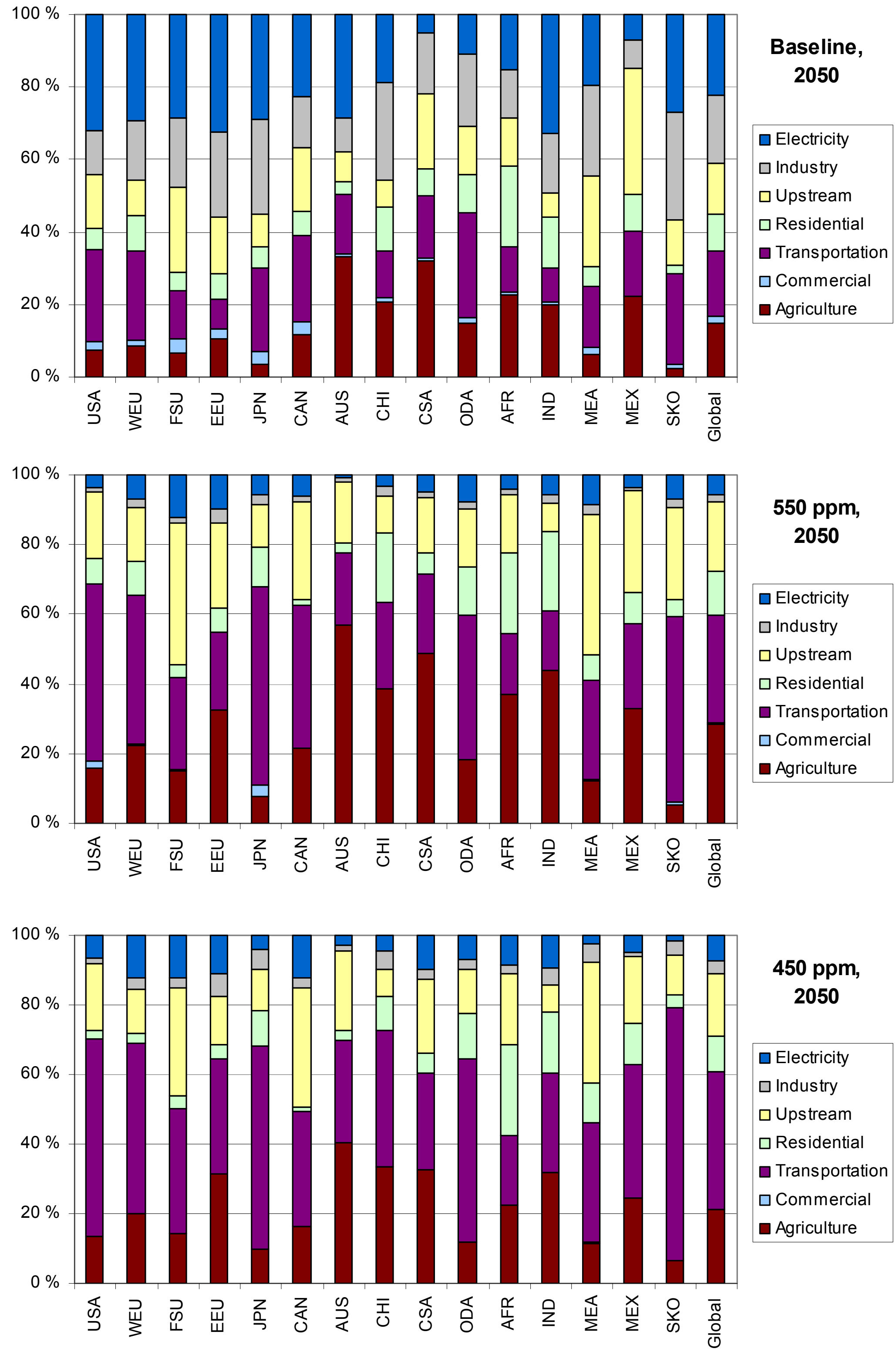

Figure A2. Regional and sectoral breakdown of regional GHG emissions in the 450 ppm (top) and 550 ppm (bottom) reduction scenarios in 2050.

Appendix B: Detailed breakdown of electricity generation

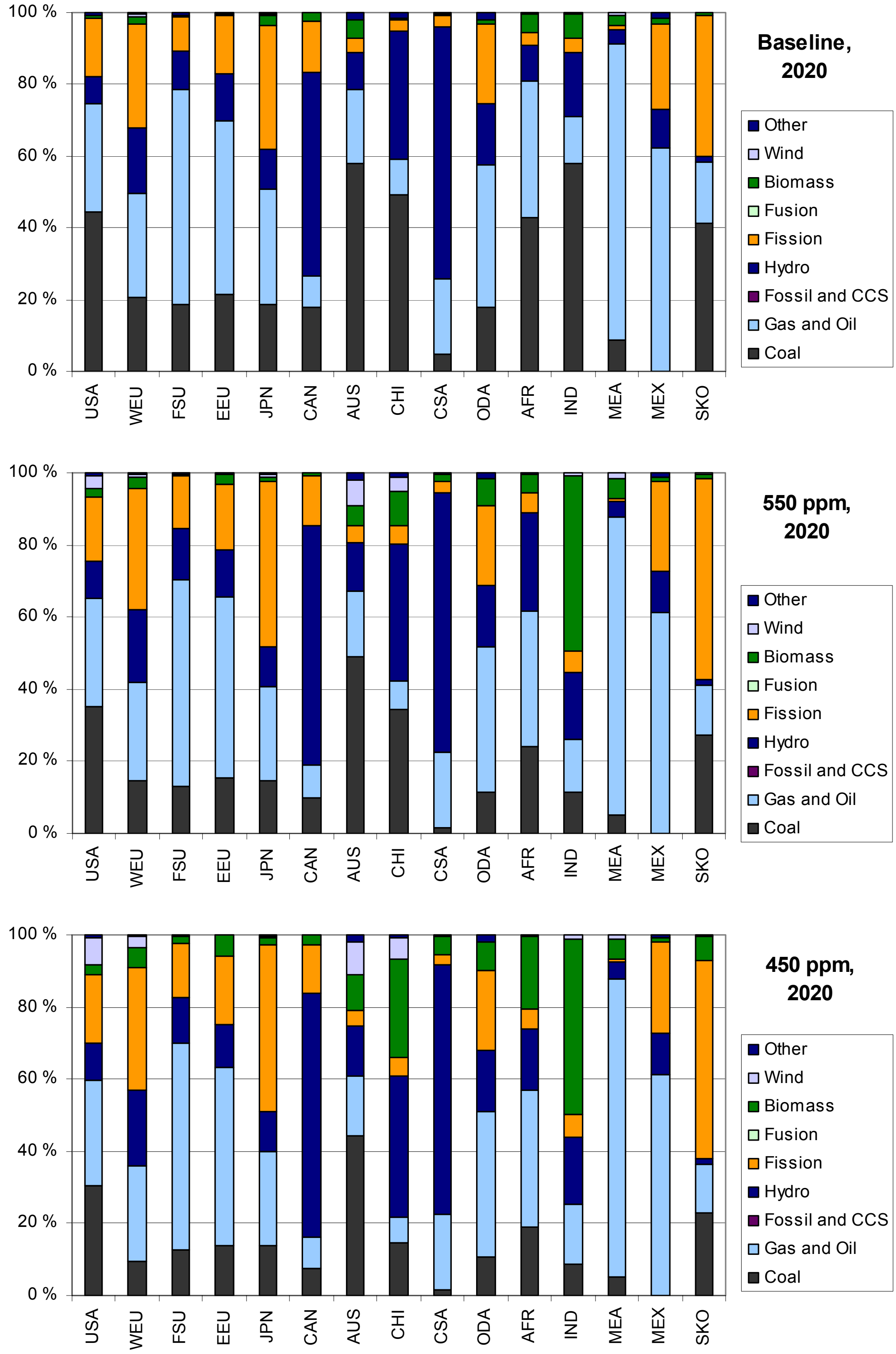

Figure B1. Regional breakdown of electricity generation in 2020 in the baseline and with 450 ppm and 550 ppm reduction targets.

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Title

Assessing the effort sharing for greenhouse gas emission reductions in ambitious global climate scenarios

Abstract

To reinforce the long-term commitment to climate change mitigation, the post-2012 climate policy framework is aimed to be completed by 2009. The new agreement needs to include a wider participation of parties, and therefore needs to address the effort sharing of countries. The mitigation capabilities and the responsibilities of countries do however vary significantly. This can, in principle, be overcome with a cap-and-trade system, with which the question of equity is addressed trough the allocation of emission allowances.

A number of effort sharing schemes have been proposed. Effort sharing however suffers from a fundamental trade-off between detail and transparency on how the emission allocations are calculated. This study addresses this problem by comparing and combining the results from a transparent but simplified effort sharing model EVOC, and a detailed and – due to its complexity – seemingly non-transparent ETSAP-TIAM energy system model. The aim of the study is to evaluate the goodness of the initial effort sharing, particularly in terms of mitigation costs experienced by different regions in the scenarios.

Based on the long-term energy-climate scenarios crafted with the TIAM model, we assess the resulting consequences in emission profiles and the energy system, concentrating especially on regional mitigation costs and emission trading. Two cases of market failures in emission trading are also considered. Finally we compare the mitigation potentials between the two models and estimate the effect of EVOC recalibration on the national emission allowances. The results of the study underline particularly the importance of detailed and reliable assumptions for the mitigation potentials of different countries in the effort sharing process.

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