PAPER VI

Effort sharing in ambitious, global climate change mitigation scenarios

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Effort sharing in ambitious, global climate change mitigation scenarios

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ABSTRACT

The post-2012 climate policy framework needs a global commitment to deep greenhouse gas emission cuts. This paper analyzes reaching ambitious emission targets up to 2050, either -10% or -50% from 1990 levels, and how the economic burden from mitigation efforts could be equitably shared between countries. The scenarios indicate a large low-cost mitigation potential in electricity and industry, while reaching low emission levels in international transportation and agricultural emissions might prove difficult. The two effort sharing approaches, Triptych and Multistage, were compared in terms of equitability and coherence. Both approaches produced an equitable cost distribution between countries, with least developed countries having negative or low costs and more developed countries having higher costs. There is, however, no definitive solution on how the costs should be balanced equitably between countries. Triptych seems to be yet more coherent than other approaches, as it can better accommodate national circumstances. Last, challenges and possible hindrances to effective mitigation and equitable effort sharing are presented. The findings underline the significance of assumptions behind effort sharing on mitigation potentials and current emissions, the challenge of sharing the effort with uncertain future allowance prices and how inefficient markets might undermine the efficiency of a cap-and-trade system.

1. Introduction

The ambitious climate change mitigation targets considered currently require global participation in the mitigation effort in the post 2012-period. Article 3.1 of the United Nations Framework Convention on Climate Change (UNFCCC) requires that the mitigation effort should be shared between the parties "on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities". In order to reach a global solution, the equity issue has to be solved. Each country has to have the impression that it is treated equitably relative to the others in order for it to participate.

The question of what is actually equitable is ambiguous, and Article 3.1 is thus open to interpretations. As an example, Ringius et al. (1998) lists the following equity concepts:

- Egalitarian—equal emissions per capita.
- Sovereign—equal reductions from, e.g., 2000.
- Horizontal—equal net change in welfare, e.g. in GDP.
- Vertical—effort dependent on ability.
- Equal responsibility—effort based on historical emissions.

In addition to equity, to achieve economic efficiency the emissions should be mitigated where least costly. Solutions to the conflict between equity and efficiency include cap-and-trade systems or harmonized emission taxes. Under perfect markets without uncertainty, the approaches should produce the same outcome. The equity issue can then be dealt with either the allocation of tradable emission allowances or the redirection of tax revenues. Due to a more simpler setting, this paper analyzes a global cap-and-trade system.

In a perfect market setting the allocation of emission allowances is merely a financial compensation. The parties are free to trade allowances and their actions are guided solely by the market price of allowances, not by how much the party initially owns allowances. Therefore in principle the mitigation costs of the parties could be adjusted through the allocation without affecting the actual mitigation measures.

The level to which the global emissions should be reduced is obviously debatable. However, as were shown by Manne and Stephan (2005), under certain conditions, the optimal level of abatement for different countries does not depend on the

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allocation of allowances. Therefore the overall abatement level and equity issues can be separated and analyzed on their own.

Given an overall emission limit, effort sharing deals with the distribution of limited emission allocations to the parties. The effort sharing process and tools used should be reliable, understandable and transparent in order to build confidence in the process. The resulting allocations, however can, and moreover should, be analyzed with more sophisticated if less transparent models.

This paper focuses on the equity of effort sharing with two exogenously assumed reduction targets that would stabilize greenhouse gas atmospheric concentrations to 485 ppm CO_2-eq and 550 ppm CO_2-eq by the end of the century. A simple and transparent tool Evolution of Commitments (EVOC) (Höhne et al., 2006) tool is used to calculate the allocation of emissions, which are then used in long-term energy-climate scenarios produced with ETSAP-TIAM (Loulou and Labriet, 2008; Loulou, 2008), a more sophisticated integrated assessment model. Though transparently documented, the TIAM may be seemingly opaque due to its size and complexity.

The stance of vertical equity with respect to economic burden from mitigation is taken here, reflecting the ‘‘respective capabilities’’ stated in Article 3.1. Then the effort sharing rule should allocate higher mitigation costs (relative to GDP) for wealthier countries, measured e.g. in terms of GDP per capita, much in the same sense as progressive taxation taxes more those with higher income. The mitigation costs considered include direct mitigation costs, changes in energy trade, allowance trade and the value of lost demand due to price elasticity; but disregard indirect macroeconomic costs, damage costs and possible benefits from avoided climate change.

Numerous mitigation scenario studies have already been made. Past studies have, however, often considered only CO_2 or higher stabilization levels for atmospheric greenhouse gas concentrations than what can currently be seen as relevant (Fisher et al., 2007). Also, a number of studies investigating the effort sharing have been conducted. The studies have, however, analyzed the effort sharing only in terms of allocated emissions and by comparing them to GDP, historical emissions or population (Miketa and Schrattenholzer, 2006; Vaillancourt and Waaub, 2004), taken only CO_2 into account (Persson et al., 2006; Russ et al., 2005), or used a simplified model with marginal abatement curves (MACs), as e.g. den Elzen et al. (2005, 2007) with the FAIR model. An exception from these, though, is den Elzen et al. (2008b), which evaluates two effort sharing rules with the FAIR model using updated MAC curves, and including also detailed analyses with the energy and land use models of IMAGE. Studies with general equilibrium models have also been carried out (Böhringer and Welsch, 2004; Peterson and Klepper, 2007) providing light on the macroeconomic effects of mitigation measures, though with less detail on specific mitigation measures.

This paper intends to address these shortcomings with a threefold purpose. First, the attainability of ambitious mitigation targets, -50% from 1990 levels, for all Kyoto-gases until 2050 are analyzed while also exploring possible bottlenecks for further mitigation. Second, the mitigation scenarios are used to evaluate two effort sharing rules, also extending the analysis of effort sharing from past studies with regard to the equitability issue. Given the varying sectoral distribution of emissions across countries, the explicit reporting of the mitigation measures in the scenarios is also significant for effort sharing. Third, challenges in effort sharing are also analyzed, including imperfect allowance markets and consideration of uncertainties.

The paper is structured as follows. Section 2 describes the models for producing the emission allocations and the energy-climate scenarios along with some main assumptions. Section 3 first outlines the main mitigation measures in the scenarios, then focuses on the main economic outcomes both in global and regional scale, and finally assesses the equity of effort sharing. In Section 4 the relevant uncertainties, two cases of allowance market imperfections and the importance of assumptions behind the effort sharing are considered. Last, Section 5 draws up conclusions and discusses the main findings.

2. The models and scenario assumptions

Two separate models were used in this study. First, EVOC, a transparent but simplified effort sharing tool of Ecofys GmbH, is used to quantify the emission allocation with the Triptych (Phylipsen et al., 1998) and Multistage (den Elzen et al., 2006) effort sharing regimes. Future energy-climate scenarios with the two reduction targets are then analyzed with the more sophisticated but complex ETSAP-TIAM, a global integrated assessment model of the TIMES family. Although the TIAM 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.

2.1. EVOC

The effort sharing is based on Triptych and Multistage calculations from EVOC (Höhne et al., 2006). These effort sharing approaches were chosen as subjects as the Triptych approach might provide a good balance between simplicity and detail, and Multistage might provide a relevant ”ladder” for developing countries to join. EVOC contains collections of data on emissions from several sources and future projections of relevant variables from the IMAGE implementation of the IPCC SRES scenarios. As emission data vary in its completeness and sectoral split, EVOC combines data from the selected sources and harmonizes it with respect to the sectoral split.

Future emissions are based on IMAGE projections of parameters, such as population, GDP (PPP), electricity consumption and industrial value added. As IMAGE projections are available only for 17 world regions, EVOC de-aggregates these data by combining it with historical values. Finally, the user can set the parameters of several effort sharing rules in order to calculate emission allocations. The main parameters used in this study are provided in the electronic annex for the paper in the publisher's website.

2.1.1. Triptych

The Triptych approach was originally developed for sharing the CO_2 mitigation effort between the EU member states using three sectors: power sector, the internationally operating energy-intensive industry and the domestically oriented sectors (Phylipsen et al., 1998), but has been updated thereafter to contain more countries (Groenenberg et al., 2001), sectors and greenhouse gases, and recently also to have multistaged commitments (den Elzen et al., 2008a).

The emission target for each sector is calculated with given assumptions on the reduction potentials in the sector. The Triptych version 6.0 that was used in the study is documented by Phylipsen et al. (2004). This version uses six sectors: Electricity, Industry, Fossil fuel production, Domestic, Agriculture and Waste. The electricity and industry sectors use parameters on efficiency, structure and income levels to calculate the emission limits. Domestic, and waste sectors use a single convergence level, given in terms of $tCO_2-eq/capita$, to which the emissions of countries converge by a given year. This is to reflect the converging living standards and practices in different countries. For fossil fuel production and agriculture, reduction levels from the baseline are assumed. In addition to this sectoral differentiation, Triptych also uses a rough income categorization with some parameters to distinguish countries with different levels of affluence.

The emission allocation of a country is then the sum of the sectoral targets. It is though critical to note that only the country level target is binding, not the sectoral targets on which the country level target is based on. Thus Triptych is not a sectoral approach per se, but uses sectoral mitigation potentials to arrive on a more accurate estimate on how much reductions are feasibly attainable in a given country and leaves the country free to choose how to pursue its target. As the Triptych approach takes into account the sectoral distribution of emissions, and even though it uses in principle uniform sectoral potentials across all countries, it has the ability to accommodate national circumstances better than most other simplified approaches. It also explicitly allows for economic growth and improving efficiency in all countries and aims to put internationally competitive industries on the same level.

2.1.2. *Multistage*

As the name suggests, in a Multistage approach the countries participate in several stages with differentiated levels of commitment (den Elzen et al., 2006). 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), and all countries agree to have commitments at a later point in time. For this study, thresholds and commitments based on per capita emissions with four stages were applied.

Least developed countries start at stage 1, which carries no commitments. At stage 2 the countries commit to sustainable development, in practice moderate reductions, e.g. 10%, from the baseline scenario. Stage 3 would involve moderate absolute targets, e.g. more stringent targets than in stage 2. The target could now also be only positively binding, so that the country could sell allowances if it reaches its target but would not be penalized if it did not. Finally, at stage 4 the country faces substantial reduction targets. As time progresses, more and more countries enter the stage 4.

In this study, the concept of Multistage effort sharing is, however, slightly abused, as the cap-and-trade system was assumed to bind all countries. Instead, the countries without binding commitments receive emission allocations according to their baseline emissions, but are then free to mitigate emissions and sell the excess allowances for profit. If this were not the case, the mitigation policy regime would lose its effectiveness.

2.2. *ETSAP-TIAM*

The energy and emission scenarios in the study were formed with the TIAM (TIMES Integrated Assessment Model) (Loulou and Labriet, 2008; Loulou, 2008), which is based on the TIMES (The Integrated MARKAL-EFOM System) modelling methodology (Loulou et al., 2005a), both developed under the IEA's Energy Technology Systems Analysis Program (ETSAP). The TIMES family of models are bottom-up type linear partial equilibrium models that calculate the market equilibrium through the maximization of the total discounted economic surplus with given external end-use demand projections. The models assume perfect markets and, in their basic form, unlimited foresight for the calculation period.

The TIAM models the whole global energy system with 15 geographical regions. Main assumptions concerning the energy system, future energy technologies, potentials and other mitigation options in the model are described by Syri et al. (2008). All Kyoto-greenhouse gases (CO_2, CH_4, N_2O and F-gases) from all anthropogenic sources are covered by the model, although emissions from land use change were not considered in this study.

The energy consumption is based on external projections of the growth of regional GDP, the population and the volume of various economic sectors, which have been harmonized to the IMAGE implementation of four SRES scenarios that are used in EVOC, ensuring consistency between the models. Inclusion of four different energy demand scenarios—marked as A1, A2, B1 and B2—provides also perspective on the effect of different assumptions on energy demand in the future.

In order to satisfy the demands, the model contains estimates on energy resources, a vast number of technology descriptions for energy production, transformation and end use, and a number of other elements, such as user-defined constraints. The flows and prices of energy commodities, including international trade for energy and emission allowances, are calculated endogenously by the model.

The model also uses price-elasticity for energy end-use demand in the mitigation scenarios, so that final energy demand reacts to changing energy prices compared to the baseline scenario. The demand elasticity for changes in energy prices was assumed to be moderate, around -0.2 for most demands and around -0.4 for aviation and maritime transport, which were assumed to be more affected by changes in energy use prices. These values are very similar to the values used by e.g. Loulou et al. (2005b) or Persson et al. (2006) with similar models. Due to this elasticity, the model can take macroeconomic feedbacks into account in a limited manner, and allows the model to reach the emission targets with lower costs than with inelastic demand. A sensitivity analysis on this by Persson et al. (2006) indeed confirmed this, and suggested that there might be also considerable regional variation in the effect of elasticity on mitigation costs. Therefore further work on the issue might be appropriate.

The model also includes a simplified climate module (Syri et al., 2008; Loulou and Labriet, 2008) that calculates changes in radiative forcing and global mean temperature with the resulting emissions. The module uses three reservoirs for CO_2 in the biosphere, first-order decay models for CH_4 and N_2O, and two heat reservoirs for calculating the temperature change. F-gases are converted into CO_2 equivalents while calculating the concentrations.

2.3. *Main scenario assumptions*

In addition to the technological and resource assumptions made in the TIAM model, assumptions on socio-economic development and the effort sharing itself are obviously important. As has many times been previously noted, e.g. in Riahi et al. (2007), the abatement effort is very dependent on the baseline scenario. With higher energy demand and emission projections, it is harder and costlier to meet a stringent emission target. Four different economic and population growth projections from the IMAGE implementation of the SRES scenarios (IPCC, 2000) were used consistently in both EVOC and TIAM. The growth of global GDP varies in the scenarios from 2.3% to 3.6% p.a. between 2000 and 2050 with regional growth rates being higher for developing and lower for developed countries. The projections were used to project the end-use energy demand in the baseline scenarios, to which the mitigation scenarios were compared to in order to calculate the mitigation costs.

Main characteristics of the two reduction targets considered are presented in Table 1. The targets were assumed to be globally binding from 2020. For calculating the resulting concentrations, radiative forcing and mean temperature increase (using 3 °C

Table 1
The implications of the two emission targets used.

Concentration in 2100	485 ppm	550 ppm
Emissions from 1990 in 2020	+20%	+30%
Emissions in 2020 (Gt CO_2−eq)	37.1	39.5
Emissions from 1990 in 2050	−50%	−10%
Emissions in 2050 (Gt CO_2−eq)	15.4	28.2
Rad. forcing in 2100 (W/m^2)	3.0	3.6
Temp. increase in 2100 (°C)	1.8	2.1

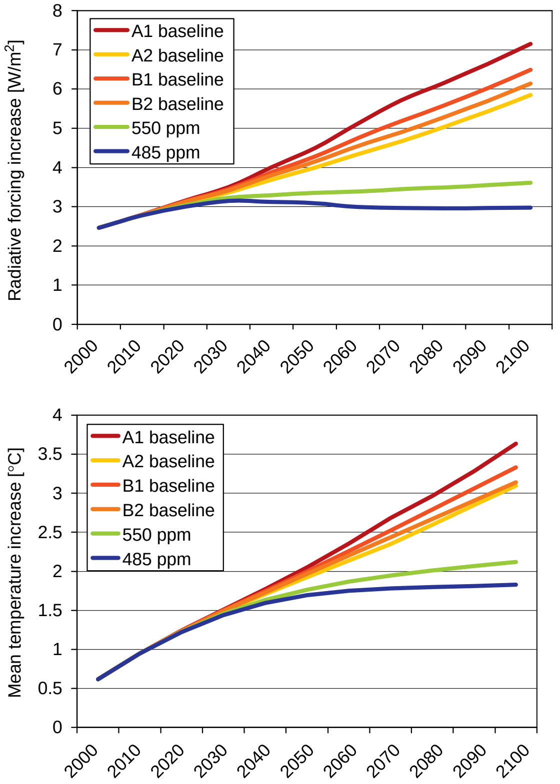

Fig. 1. Increase in radiative forcing (W/m^2, top) and global mean temperature (°C, bottom) in the four baseline scenarios and with the two mitigation scenarios.

climate sensitivity) up to 2100, the emission target of 2050 was assumed constant for the period between 2050 and 2100. If further reductions would be made post-2050, though, concentrations below 485 and 550 ppm would be attainable by 2100.

The more stringent target falls in the high end of IPCC Category I of stabilization levels (Fisher et al., 2007). It overshoots first to 505 ppm CO_2−eq in 2030 before declining to levels around and below 490 ppm, as can be seen in Fig. 1. The figure also presents the global mean temperature increase in baseline and reduction cases. With the 485 ppm target the temperature stabilizes during the century, whereas with the 550 ppm target it is still increasing in 2100 and would probably stabilize around 2.5 °C later on.

It is, however, critical to note that the measures in the scenarios do not affect land use change and forestry emissions. An undisturbed baseline scenario was assumed for deforestation, thus increasing the overall CO_2 emissions and concentrations. As the focus here is on effort sharing, and as the uncertainties of both deforestation emissions and afforestation measures are very large, it was natural to disregard these.

Fig. 2 presents the emission allocation, relative to 2000 emissions, in 2020 and 2050 for the 15 different countries or country groups in TIAM. The bars present the median of the four economic growth scenarios. The approaches allocate, respectively, 10–50% reductions for Annex I in 2020 and 60–95% reductions in 2050. Non-Annex I regions may increase their emissions up to 2020 by varying amounts, whereas in 2050 only the least developed regions receive allocations above their 2000 emission levels. Also it can be noted that the Multistage approach generally allocates more emissions to the least developed countries in 2050 than Triptych.

3. Scenarios

3.1. Emissions and mitigation measures

Of all the eight different mitigation scenarios created, the moderate growth B2 scenarios with both reduction targets are used for illustrating the mitigation measures. Fig. 3 portrays the emission profiles in both cases, separately for combustion and process emissions. As can be seen from Fig. 3, the electricity sector provides the largest cost-efficient mitigation potential. Also large emission reductions are carried out in the industrial sector and a number of measures also in the other sectors. Below is a list of main measures in five sectors:

- Electricity: Phase-out of coal; strong adoption of wind power and biomass; slight increase in hydro and nuclear from baseline; gas and coal with CCS.
- Industry: Phase-out of fossil fuels, especially coal; CCS; biomass, also combined with CCS; N_2O from chemical industries; blended cements replacing clinker.
- Transportation: Fuel efficiency; natural gas on heavier road vehicles; later hydrogen or electricity.
- Residential and commercial: The energy mix shifting to electricity and heat; efficiency; considerable potential on waste CH_4.
- Agriculture: Limited low-cost potential in all categories; extensive reductions challenging e.g. in cattle and rice paddy CH_4 and soil N_2O.

3.1.1. Electricity and industry

Emission reductions in electricity production and industry are perhaps the most straightforward and extensively studied. Phase-out of coal and other fossil fuels, or their use in conjunction with CCS, would contribute to the most of the emission reductions. Also, sustainably grown bio-energy with CCS could provide negative emissions.

Most electricity generating technologies, such as wind power, nuclear energy and biomass, are mature and already in the market. In the medium-long term, the only technology currently still in the demonstration phase is CCS. In 2050, however, there would be a need for novel production technologies as fusion power, though being very costly, emerged in 2050 in the scenarios, especially with the 485 ppm target.

Changes and improvements in industrial processes, such as increased use of steel scrap or inert anodes in aluminium smelters, would also contribute to the reductions. Blended cement and clinker kilns with CCS could be used in cement production. Also, N_2O emission reductions using thermal destruction and catalytic

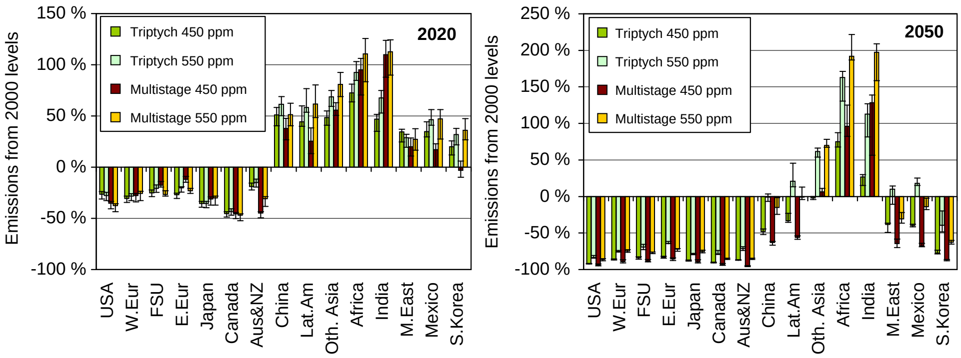

Fig. 2. Emission allocation, relative to 2000 emissions, with the Triptych and Multistage effort sharing approaches and two reduction targets in 2020 (left) and 2050 (right). The error bars correspond to the range of values with four baseline scenarios.

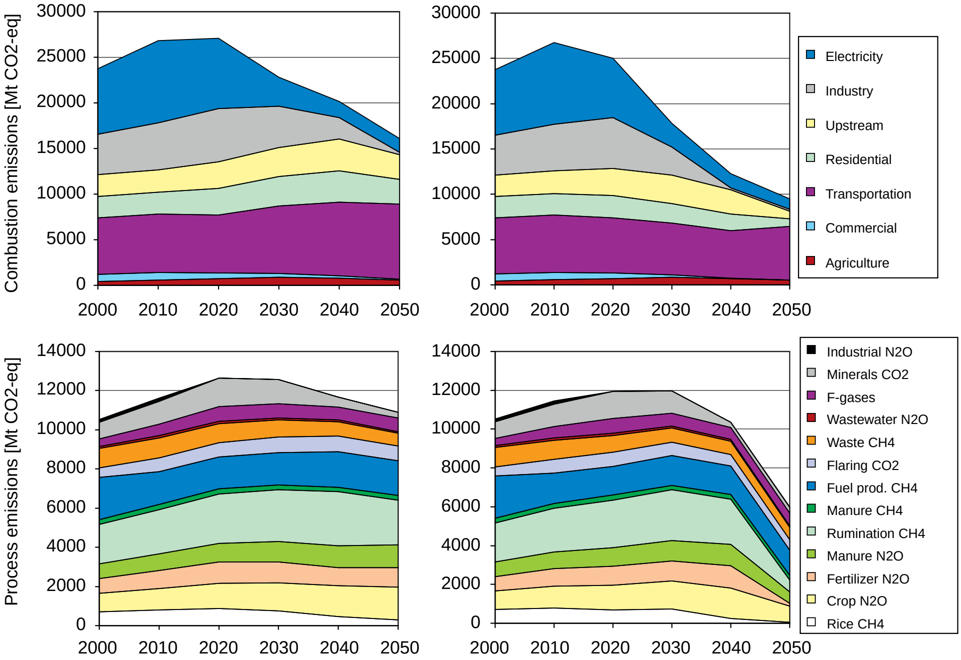

Fig. 3. Global greenhouse gas emissions with the 550 ppm (left) and 485 ppm (right) mitigation targets, split between combustion (top) and process-based (bottom).

reduction, respectively, in adipic and nitric acid industries are one of the first mitigation measures taken.

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 due to the demand price-elasticity. The rising carbon price affects production in the long run, and industrial production is on average 12% below the baselines with the 485 ppm target in 2050. With a 2% annual growth rate in industry output, this would equal a rather small 0.25% reduction in the annual growth rate.

3.1.2. *Transportation*

In road transportation deep reduction through a shift to natural gas, electricity/hydrogen and biofuels (when sustainably produced) should be feasible. Rising demand could however turn the decreasing trend in road transportation emission again to a rise by 2050 even with the low-emission technologies.

International transportation—especially aviation—might also pose more difficulties. Even though the fuel efficiency has improved in aviation, development extrapolated from the historical pace is not sufficient to stabilize emissions with the projected growth in aviation demand (Macintosh and Wallace, 2009). Clearly, then, if the emissions are deemed to decrease, also the demand has to decrease to some extent.

Studies and demonstrations with liquid hydrogen and biofuels (Fischer–Tropsch kerosene) as alternative aviation fuels have been conducted. Both fuels, however, have their difficulties. Hydrogen airplanes involve large technical and operational challenges due to the low volumetric energy density and the need for pressurized cryogenic tanks. The Fischer–Tropsch process is technologically mature and the product resembles fossil kerosene. The challenge with biofuels is, however, of price and quantity. The baseline final energy demand for aviation and shipping equalled roughly 60 EJ/a in 2050. As the required primary energy would be higher, it might prove hard to increase sufficiently the bioenergy supply—roughly at 130 EJ/a in the 485 ppm scenarios in 2050—even though the rising allowance prices might render biofuels competitive.

Due to these challenges, the technologies were excluded from the scenarios, and, as a result, the level of transportation emission remains relatively constant throughout the 485 ppm scenario.

3.1.3. *Agriculture*

Important mitigation potential exists in agriculture, often in the form of improved management practices. Mitigation measures have been analyzed for example in the EMF-21 study (DeAngelo et al., 2006), on which the mitigation measures in the TIAM model are mostly based on. The applicability of most measures is, however, only partial, and agricultural emissions tend to continue their growth in the reduction scenarios.

When very stringent emission targets, such as -50% reductions from 1990, are pursued, also agricultural emission have to be reduced considerably. If the potentials of technological and management options do not improve substantially from those assessed in DeAngelo et al. (2006), a shift towards less emitting agricultural products, e.g. cattle to poultry and swine and rice to other cereals, might be necessary.

With sufficiently high allowance prices this might happen directly through the market mechanism. As an example, assuming emissions of 1.5 t $CO_2-eq/head/a$ (IPCC, 2006) for beef cattle and 200 kg meat yield after two years, an allowance price of 500$\$_{2000}$/t CO_2 would increase the producer price by 7.5$\$_{2000}$/kg meat. Similarly, taken the default emission factor of 1.3 kg CH_4 /ha/d for rice paddy (IPCC, 2006) and a production of 4 t rice/ha/a (FAO, 2009), the producer price would increase by 1.2$\$_{2000}$ /kg rice due to the emissions. Being roughly 2–5 and 10 times higher than the producer prices in 2000 (FAO, 2009), respectively, for cattle meat and rice, price increases of this magnitude might cut consumption considerably and shift it to lower emitting substitutes.

As the emission sources are very dispersed and mostly concentrated 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 and dependences on local conditions with agricultural emissions, especially concerning N_2O.

A very important source of potential mitigation measures, reduced deforestation and afforestation, were not considered in the scenarios. As the estimates both on emissions from deforestation and mitigation options are very uncertain, these emissions and mitigation measures might distort the analysis of effort sharing substantially. On the global scale, the exclusion of these measures, however, increases the mitigation costs in the scenarios, perhaps even drastically.

3.2. *Mitigation costs*

The main issue in effort sharing is how to divide the global mitigation costs between the countries. Clearly, an important factor here is the total level of costs. The effect of different baseline scenarios and reduction targets on the mitigation costs has been noted in previous studies (e.g. Riahi et al., 2007). This arises from different demand levels for end-use commodities and the system costs in the baseline scenario.

An often used measure of economic burden is the mitigation costs, i.e. the difference in energy system costs between baseline and mitigation scenarios, divided by the projected global GDP. Fig. 4 portrays this measure on global scale in 2020 and 2050 for a spectrum of mitigation targets and four socioeconomical scenarios. The more ambitious end of the reduction targets equals the 485 ppm mitigation target and the more lax the 550 ppm target, the targets between being linear interpolations of the 485 and 550 ppm targets.

As the economic burden of mitigation is shared through the allocation and trade of emission allowances, the price of allowances is critical for effort sharing. Fig. 5 portrays the average price of allowances between 2020 and 2050 in the scenarios with both mitigation targets. As can be seen from the figure, the price is projected to rise steeply after 2030 with the tightening emission limits, especially with the 485 ppm target.

3.3. *Effort sharing*

Fig. 6 presents regional mitigation and emission trade costs in 2020 and 2050. A numerical table with additional details is

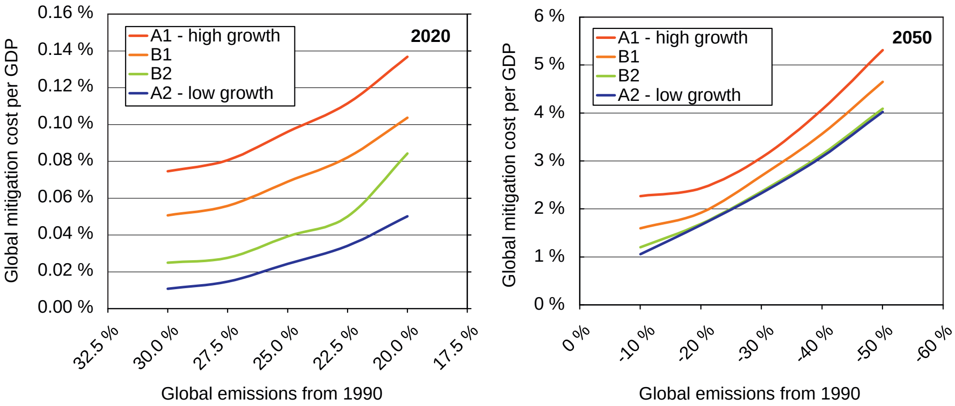

Fig. 4. Global mitigation costs relative to global GDP (*Y*-axis) in 2020 (left) and 2050 (right), with the different economic growth scenarios and emission reduction targets (relative to 1990 emissions, *X*-axis).

provided in Appendix A. Both effort sharing rules allocate costs for Annex I countries in 2020 (with the exclusion of Eastern Europe), costs around zero for more developed non-Annex I countries, and gains for least developed countries as a result of selling emission allowances. In 2050, Annex I countries, especially Australia and Russia (as a part of FSU) with the 485 ppm target, face relatively high costs. Also most non-Annex I countries face positive costs, and only India and Africa are able to gain financially from the effort sharing. The costs for Annex I regions are generally doubled with the 485 ppm target in 2050 compared to the 550 ppm target. A clear outlier from the overall pattern with all effort sharing rules is Middle East, the situation of which is analyzed briefly later.

For most regions the most important factor in the costs is allowance trade. Other factors include increased investment costs, reductions in fuel and operation costs and welfare losses as demand adjusts to higher energy prices. The volume of allowance trade can be substantial for some regions, especially in 2050 with the 485 ppm target when allowance prices are very high. The largest net seller in 2050 was India, which was able to sell allowances for from 1 Gt CO_2−eq (Triptych 485 ppm) to 4 Gt CO_2−eq (Multistage 550 ppm). Assuming a price of 500$/t, as an example, India would annually gain from 1% to over 10% of its baseline GDP from allowance sales in 2050, depending on the baseline. This would obviously have drastic impacts on the global economic system. For comparison, India's current account balance has been between -2.5% and 1.5% of GDP since 1980.

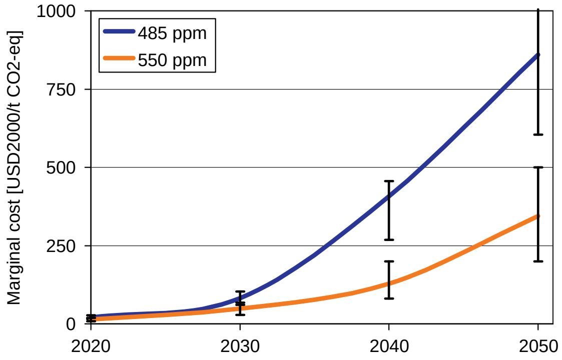

Fig. 5. Marginal costs of emission allowances ($\$_{2000}$/t CO_2-eq) in the scenarios. The error bars correspond to the range of values with four baseline scenarios.

As the Article 3.1 of the convention implies, the developed nations should take a lead in the mitigation effort. In order to assess the effort sharing in the light of the vertical equity principle, the regional mitigation costs were compared to the projected GDP per capita figures. Besides being equitable on a broad level, effort sharing should obviously be coherent by allocating similar costs for equally wealthy countries. An equitable and coherent effort sharing should then put the countries on an up-sloping line or a curve in the GDP per capita—mitigation cost plane. The slope of the curve should then be the subject of debate, that is, how much the more wealthy nations are seen to be responsible of taking on the costs.

In order to build more perspective, two very opposing effort sharing regimes are also portrayed in addition to Triptych and Multistage. An egalitarian approach, equal emissions per capita, has often been supported by developing countries. On the other hand, a grandfathering approach would be in line with the sovereign equity principle and favor the developed countries.

Fig. 7 portrays the regional mitigation costs against their GDP per capita projections, for 2020 and 2050 and both reduction targets. The figure includes also smoothed averages using Gaussian kernel smoothing to give better view on the overall equitability of each effort sharing regime.

Middle East, being an outlier from the overall pattern, was excluded from the kernel smoothing procedure. The mitigation costs in Middle East arise to a large extent from lower revenues from oil trade, resulting from a lower exports and oil price compared to the baseline scenarios, from 8% to 25% depending on the baseline and emission target, a phenomenon noted also by den Elzen et al. (2008b). Middle East is, however, a very heterogeneous group and the more wealthy oil-exporting countries, notably Saudi Arabia, Emirates, Kuwait and Qatar, constitute a relatively large share of both oil production and GDP in the region but only a small share of population, thus distorting the comparison between wealth and mitigation costs for Middle East.

As can be seen from Fig. 7, the differences between Triptych and Multistage in 2020 are relatively minor and fall between Per capita and Grandfathering approaches. The costs distribute equitably in the spirit of Article 3.1 with Triptych and Multistage approaches, with least developed regions having small negative costs, resulting from allowance sales, and developed regions having positive costs. While both approaches have a good coherence in costs vs. wealth, Triptych slightly outperforms Multistage in this sense. As was initially assumed, Per capita is very favorable to the least developed regions and Grandfathering for the developed.

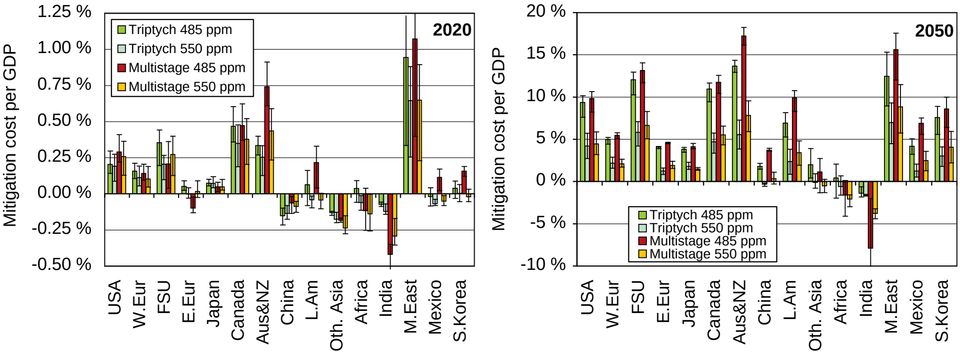

Fig. 6. Regional mitigation costs relative to their baseline GDP in 2020 (left) and 2050 (right). The error bars correspond to the range of values with four baseline scenarios.

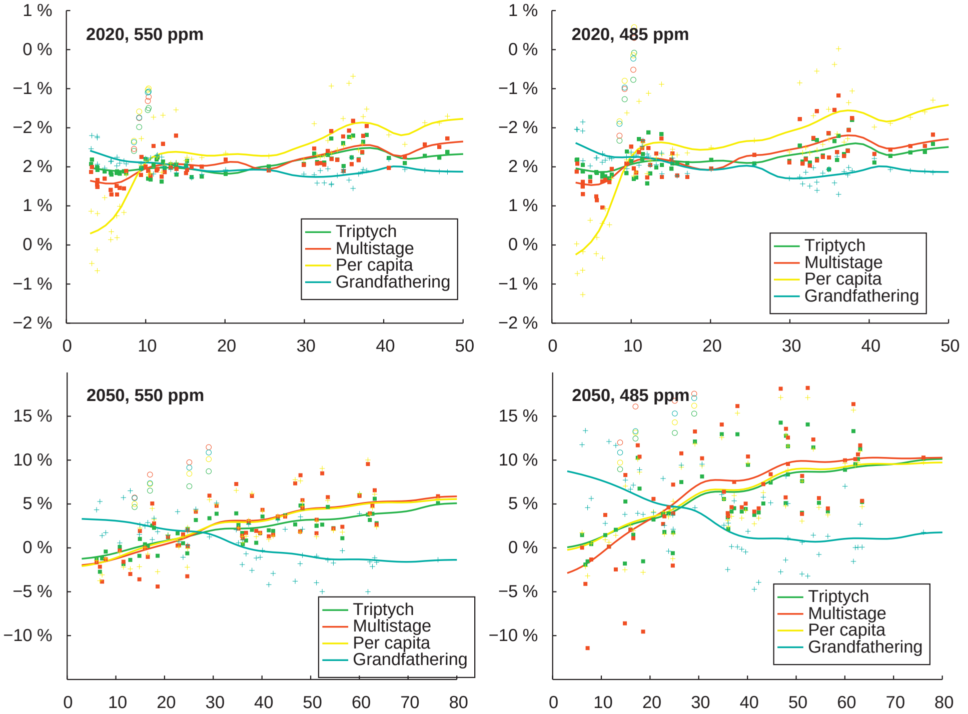

Fig. 7. Regional mitigation costs relative to GDP (*y*-axis) against regional GDP per capita ($1000\$_{2000}$(PPP)/cap/a, *x*-axis), with four effort sharing rules and two mitigation targets in 2020 and 2050. Each dot or cross represents a single region with one of the four economic scenarios used. The solid lines are average values calculated with gaussian kernel smoothing. Middle East, marked with circles, has been excluded from the smoothed lines.

In 2050 the Triptych, Multistage and Per capita approaches produce very similar results on average, but Triptych exhibits some differences from the other two in the regional scale. As the emission converge to given emission per capita levels in the Multistage by 2050, the results between Multistage and Per capita approaches are very similar also in the regional level. However, Multistage is even more beneficial for least developed regions than the Per capita approach with the 485 ppm target, as some countries are still below the fourth stage threshold.

In the Triptych approach the sectoral emission converge to either "low" or "near-zero" levels (electricity, fossil fuel production and industry) or to given per capita levels (other sectors). Agriculture can also be included in the latter category, as the targets are defined as reductions from baseline emissions, which in turn are driven by population growth. This explains the similarity of Triptych and Per capita approaches, as a large share of the emissions allowances is allocated in per-capita term, especially with the 485 ppm target.

In terms of coherence Triptych again outperforms the other approaches clearly with the 550 ppm target in 2050, but not quite so with the 485 ppm target. This is again explained by the dominance of per-capita based sectoral targets, which is greater with the 485 ppm target. The coherence of Triptych is based on its ability to take into account the sectoral distribution of emissions in different countries, and thus also the countries' mitigation abilities. If the allowances are allocated mostly in per-capita terms, as with the 485 ppm target, coherence deteriorates.

3.4. *Comparison to other studies*

Comparison of the results to previous studies using different models reveals the importance of background assumptions used. Different studies can be distinguished with regard to the model used, baselines, available mitigation potentials, emission targets and effort sharing rules used.

Two different studies (van Vuuren et al., 2007; den Elzen et al., 2008b), using the IMAGE system in slightly different scenario settings, provide a good reference point. The emission levels, somewhat above 20 Gt CO_2-eq in 2050, fall between our 485 and 550 ppm targets. The marginal costs in den Elzen et al. (2008b) were between 125 and 270\$/tCO_2-eq, which is generally lower than the range with our 550 ppm scenarios. The global costs were quite similar, around 1–2.5% of global GDP in 2050. The marginal and global costs in van Vuuren et al. (2007) with B2 fall into both of these ranges.

The differences in costs relative to the stringency of the emission target were attributed mostly to the assumptions on non-CO_2 mitigation and bioenergy supply potentials. The non-CO_2 potentials in the IMAGE model are based on an extension of the EMF-21 results (Lucas et al., 2007), and include rather optimistic estimates compared to those in the TIAM model. Also, bioenergy supply was limited to 500 EJ/a in den Elzen et al. (2008b), which is roughly four times larger than in our scenarios. Estimates both on bioenergy and non-CO_2 mitigation potentials are very uncertain, as was also acknowledged by den Elzen et al. (2008b). These assumptions have, however, a significant impact on the results, especially when deep emission reductions are assessed.

A comparison to Riahi et al. (2007), a mitigation scenario study using the MESSAGE model, is more difficult as the costs are reported only in terms of system costs and GDP losses, which is not directly translatable to the mitigation costs per GDP measure. However, an earlier study (Rao and Riahi, 2006) explores scenarios aiming at 4.5 and 3 W/m^2 radiative forcing targets by 2100 with multi-gas strategies. Although the radiative forcing targets equal those attained in the scenarios presented here, the emission profiles are very different with emissions exceeding 30 Gt CO_2−eq in 2050 in the MESSAGE scenarios and declining more later on. As a result, the marginal costs of emissions are also substantially lower in 2050, slightly above 100$/t CO_2-eq, but reach levels around 750$/t CO_2−eq by 2100.

The optimal profile of emission reductions is debatable, and cost-optimizing models such as TIMES and MESSAGE tend to postpone mitigation measures due to discounting if e.g. a radiative forcing or a temperature target is given instead of fixed annual caps. This can be also seen in a previous study with the TIAM modelling system (Syri et al., 2008), which investigated the optimal strategy for limiting global mean temperature increase below 2 °C by 2100. The optimization resulted with emissions around 30 Gt CO_2−eq in 2050, a level substantially higher than used in this study. However, as was also found by Syri et al. (2008), if stochastic optimization is used in the face of uncertainty in the climate sensitivity parameter, an optimal risk-hedging strategy would be to limit emissions to around 20 Gt CO_2−eq by 2050 in order to satisfy the 2 °C target. This result is therefore much in favor of targets lower than e.g. in Rao and Riahi (2006).

With regard to effort sharing, the results were compared to den Elzen et al. (2008b), which assessed Multistage and Contract and Converge effort sharing approaches. Even though having lower global mitigation costs, the patterns on how the cost is distributed is relatively similar to ours. Developed countries receive higher costs and least developed Sub-Saharan Africa and South Asia negative costs in 2050. Also, the countries under the former Soviet Union (FSU) region and Middle East fall outside the general pattern with higher costs, the former especially with Multistage effort sharing.

4. Challenges in effort sharing

Even if the effort can be shared in theory in a predetermined way, there are reasons why the economic burden might not distribute as planned. Perhaps the most evident is uncertainty in mitigation costs and the future price of allowances. In addition to this, the allowance market might not be perfect, which has been assumed in the analysis above, and this is analyzed in the case of transaction costs and imperfect participation to the market.

Also, the allocation of emission allowances is based on estimates on current emissions and sectoral mitigation potentials in the Triptych approach, but these parameters are not very well known. Although this uncertainty does not affect the analysis and methods used in this study as the allocation was taken as given, the allocation is obviously critical in defining the regional costs.

4.1. Imperfect markets

Two cases of market imperfections were considered to illustrate possible market-based hindrances for effort sharing. The first case introduces transaction costs in allowance trading, inhibiting the efficient functioning of markets. In the second case, a large net seller of allowances refuses to sell allowances to the market. Both cases were assessed in 2020 with the B2 growth scenario, 550 ppm mitigation target and Triptych effort sharing.

The introduction of transaction costs to the allowance market results with a situation where the sellers' and buyers' marginal abatement costs differ by the amount of the cost introduced. The cost might arise from numerous reasons, including imperfect information, market frictions or the faulting of the pricing mechanism, e.g. due to speculation. Some actors also 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, volatile prices provide an incentive for risk averse hedging strategies that are somewhat costlier.

Due to the large number of potential sources, transaction costs are hard to quantify or forecast. To analyze its effect on the market, a quantification is, however, needed and as a rough guess a 10$/t CO_2−eq transaction cost was imposed to the markets. This can be seen as a moderate increase to the allowance price of 15$/t in 2020 in the setting without transaction costs. The cost reduced both the volume of emission trading by 20%, increased the costs of allowances by 23% (including the transaction cost), and doubled the global mitigation costs.

In the other case considered, a large net seller was assumed to refrain from trading its allowances. This can be conceptually contrasted from a scenario with limited participation in the overall mitigation effort, which has been analyzed previously e.g. by Edmonds et al. (2008). Even though all countries might comply with quantitative emission targets, there exists a risk that they will not participate in the allowance market in an efficient manner. China was chosen for this role for illustrative purposes, as it was the largest net seller of allowances in 2020 with Triptych effort sharing. 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.

In theory, a country cannot gain financially by restricting its allowance trading. Such action can be however easily justified. China faced some 40% increase in electricity prices and 90% increase in coal use costs 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 from selling the allowances. Solutions to this dilemma might include using some of the emission trade revenues to subsidize clean energy production or consumption or a fragmented distribution of allowances to different actors in the allowance market.

On the global level, the setting resulted in one-third higher price for emission allowances compared to the basic setting, and a doubling of global mitigation costs. In contrast a surplus, though small, of allowances in China rendered their price to zero. In this scenario China loses its revenues from emissions trading but gains slightly on energy prices. Even though the total cost is slightly less than in the baseline, it is—as theory suggests—higher than in the case where China is selling its allowances.

4.2. Uncertainties

Uncertainties relevant for effort sharing arise from the baseline scenario, direct mitigation costs (technological and resource uncertainties) and allowance prices. Of these, the first was—to some extent—included in the analysis above with four baselines.

Technological and resource uncertainties affect in a simplified sense the marginal abatement curve (MAC) of a country. The effect on effort sharing is might be, however, small, as most technologies affect all countries. Then, a change in the costs or potential of a given technology affects effort sharing with countries that are more dependent on that technology than other countries. Such findings have been presented by den Elzen et al. (2005), where a second set of MAC's in the FAIR model raised uniformly the costs of all regions, although den Elzen et al. (2008b) noted that a specific technology's cost, CCS's in their case, might affect some countries more. The marginal mitigation cost is, however, also the basis for the price of allowances.

Allowance prices might also carry additional uncertainty due to market imperfections as was suggested in Section 4.1. The uncertainty in future allowance prices has important implications on the attainability of equitable effort sharing. The allowances have to be allocated to the countries in advance, and their value can be observed only later on.

As the price varies from 20% to 50% around the average between the scenarios with different baselines, and as the allowance trade might constitute a large share of region's mitigation costs, the price variability might affect the regional mitigation costs to a large extent. As the allowance trade costs are second order results from the model, they are more uncertain than most other results presented. However, with a given effort sharing regime, the amount of allowances a country buys or sells is relatively stable across the scenarios. In contrast, the price is very dependent on the background growth scenario. Uncertainties on marginal mitigation costs are in turn much larger for the more ambitious 485 ppm mitigation scenario, in which more unconventional measures have to be taken in order to reach the emission target.

4.3. Estimates of current emissions

Inventories or statistics on current emissions are far from perfect and subject to uncertainties, especially in the case of developing countries. Several organizations are providing emission estimates. Parties to the UN-FCCC are obliged to report their emission inventories, for Annex I parties annually and for the developing countries on a less frequent basis. The IEA publishes a global emission inventory from fuel combustion based on the energy statistics it gathers, supplemented with non-combustion emission estimates from the Emission Database for Global Atmospheric Research (EDGAR). Also, US-EPA has estimated global non-CO_2 emissions.

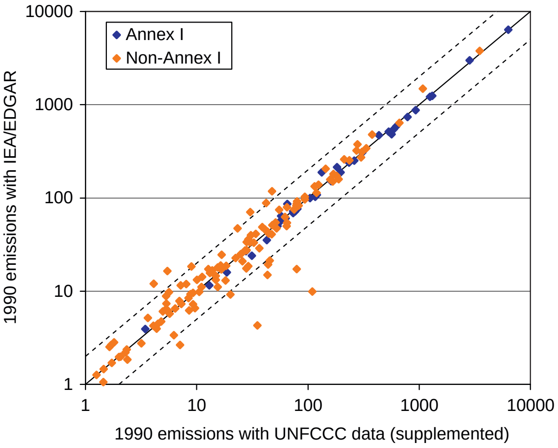

Fig. 8. Emission estimates for 1990 for different countries (Mt CO_2-eq, logarithmic scale) based on UN-FCCC (*X*-axis) or IEA/EDGAR (*Y*-axis). The dashed lines indicate points where one estimate is twice the magnitude of the other estimate.

The different datasets can exhibit considerable differences in their estimates. Fig. 8 presents emissions in the EVOC database with UN-FCCC and IEA/EDGAR-based data. Large deviations can be seen from the diagonal line, representing equal estimates between the sources, and for many individual countries the difference is over 100%, indicated by the dashed lines in the figure. As the effort sharing is based on these emission estimates, through sectoral projections in Triptych and emissions per capita in Multistage, the accuracy of emission estimates is material. Using different historical emission estimates might imply differences of several tens of percentage points on the allowances a country receives.

4.4. Assumptions behind the effort sharing

Obviously, effort sharing with the Triptych and Multistage approaches is dependent on the underlying assumption and parameter choices which define the allocation of emission allowances. Therefore a risk exists that if the parameters are inaccurate, the effort sharing can end up being erroneous.

This is especially problematic for the Triptych approach, as it is the more complicated one from the approaches assessed in this paper. The effort sharing with Triptych is based on assumptions on feasible mitigation potentials in each sector, which are in turn very uncertain in the very long term as noted in Section 3.1. Then, if the actual potentials in the future differ from those assumed, the emission allocation favors the countries, for which the mitigation potential has been underestimated.

During the study a notable difference in sectoral mitigation potential estimates—especially in agriculture—between EVOC and TIAM was noted, which prompted to a recalibration of EVOC to match the results from TIAM. Fig. 9 presents the results from EVOC for Triptych 550 ppm effort sharing in 2020 and 2050 before and after the recalibration. This recalibration had a large effect especially for certain countries. As an example, Australia received 66% more allowances in 2050 after the recalibration, reducing its economic burden substantially. A difference of this magnitude highlights clearly the importance of assumptions used in the effort sharing process.

5. Conclusions and discussion

This study has analyzed global effort sharing of climate change mitigation with Triptych and Multistage effort sharing rules and two mitigation scenarios aiming at -10% and -50% reductions from 1990 levels by 2050, leading to concentrations of 550 ppm CO_2-eq and 485 ppm CO_2-eq by 2100, respectively. Being simple and transparent, the EVOC tool of Ecofys GmbH was used for calculating Triptych and Multistage emission allocations, while and ETSAP-TIAM, a sophisticated but complex global energy system model of the TIMES family was used for creating the scenarios.

The available mitigation measures and their costs is crucial also for effort sharing, as the source distribution of emissions varies between countries and therefore regional mitigation potentials depend on the technological assumptions and resource estimates. Due to this, an explicit description of reduction measures undertaken in the scenarios was given. Most of the reductions were realized in electricity generation and industry. In other sectors numerous measures, however, mostly with limited potentials, were taken.

In the case of ambitious emission reductions, more unconventional measures have to be used. As many measures in transportation and agriculture were deemed to have limited mitigation potentials, reduced demand or substitution with lower

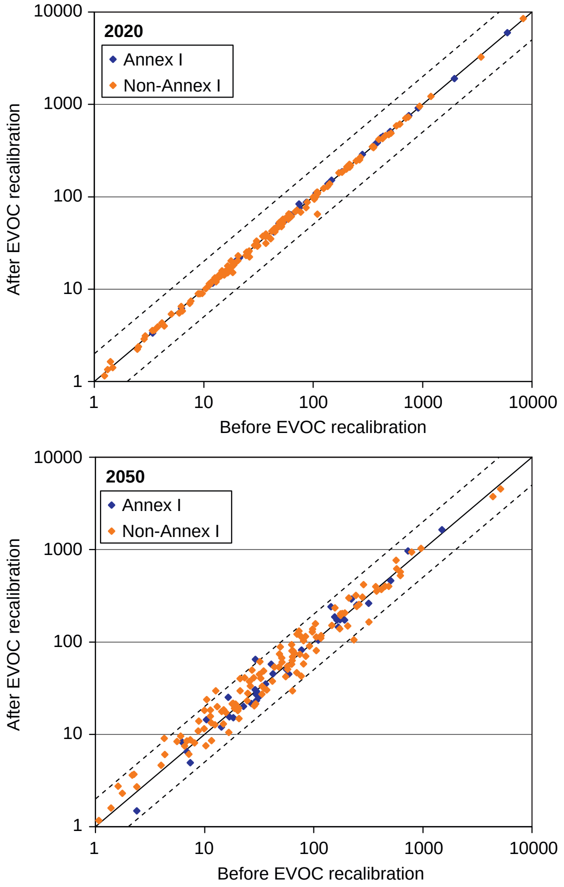

Fig. 9. Emission allocations (Mt CO_2-eq, logarithmic scale) with Triptych 550 ppm effort sharing before (*X*-axis) and after (*Y*-axis) EVOC recalibration in 2020 (top) and 2050 (bottom). The dashed lines indicate points where one estimate is twice the magnitude of the other estimate.

emitting alternatives was the only alternative for sufficient emission reductions. This was particularly the case with aviation, cattle and rice. The use of unconventional measures, however, also increases the uncertainty on mitigation costs and future allowance prices, rendering equitable effort sharing a challenging task.

The mitigation costs in the scenarios were relatively high compared to previous studies, reaching even 4–5% of global GDP with the 485 ppm target, by 2050. Also, the price of allowances was high, reaching even 1000$\$_{2000}$/t in 2050 with the 485 ppm target but being very dependent on the baseline scenario used. After accounting for differing reduction targets, the cost differences were identified to arise from less optimistic non-CO_2 mitigation potentials and the exclusion of afforestation options in this study. Although deforestation and afforestation are problematic for effort sharing due to the large uncertainties involved, they might be critical for reaching deep mitigation targets cost-efficiently.

Triptych and Multistage both allocate moderate reductions for Annex I and allow non-Annex I emissions to increase from 2000 levels by 2020. In 2050, Annex I faces very stringent targets around 80% from 2000 emissions, and only for the least developed non-Annex I regions the allowances exceeded their 2000 emissions. This is reflected also in mitigation costs with Annex I having positive costs and most or some non-Annex I regions having net gains due to allowance sales. Emission trading proved to be the most important single factor in the costs for most regions. The most extreme case was India in 2050, which was able to gain from 1% to over 10% of its baseline GDP from allowance sales.

A comparison between the economic burden the regions face and their abilities, by using GDP (PPP) per capita as a wealth measure, showed that both Triptych and Multistage produce equitable costs, although the balance of favoring the least developed and penalizing the most developed is obviously debatable. Overall, Triptych exhibited more moderate costs than Multistage for Annex I while still providing gains for non-Annex I, and might be thus be acceptable for both Annex I and non-Annex I. Triptych also exhibited higher coherence, i.e. the effort of individual regions varied less from the average. This highlights that an approach not taking into account the sectoral distribution of emissions and differing mitigation potentials can not adequately produce an equitable outcome. The coherence of Triptych did, however, degrade with the more stringent target, as the allocations are then mostly based on per-capita-based targets also with the Triptych approach.

Even if the effort can be shared equitably in theory, it might prove hard in practice. The future price of allowances varied considerably depending on the baseline, and studies with different models, and thus different assumptions, give even a wider range of possible price projections. A remark was also made on the data and assumptions behind effort sharing. Emissions estimates for especially non-Annex I are very uncertain, which makes effort sharing based on historical or projected emissions problematic. Also, if the effort sharing method specifies mitigation potentials in some form, as in the Triptych approach, these estimates have to be reliable, as was indicated by the Triptych recalibration experiment.

Given these uncertainties, fixing allowance allocations in the very long term might not be reasonable. As the mitigation costs cannot be accurately observed in reality, correcting distortions later on by reassessing the allocations would be challenging.

The analysis presented here has still some limitations. The partial equilibrium approach, while providing a detailed picture on the energy system, does not include any feedback effects from the rest of the economy. Effort sharing, especially in the extreme cases, might involve large wealth redistributions through allowance markets, affecting affluence levels and energy demand. Also, a high price of emissions is likely to induce structural change in the economy. Should the demand and production structures adjust to the cost of carbon, the mitigation costs then would be lower than reported here. With the TIAM model, the only possible adjustment is reduced demand, i.e. welfare loss, instead of e.g. demand substitution.

What was also not considered here, is the avoided damage costs from climate change through mitigation. Potential damage costs and adaptation capabilities vary largely between countries, and therefore should be also included in the analysis. This would, however, make the results unreliable due to the large uncertainties. Linking effort sharing to the funding of adaptation and technology transfer would still be reasonable, as all deal with transferring resources to the least developed and most vulnerable regions.

Last, the smooth operation of allowance markets and full participation of the parties is essential for cost-effectiveness.

Cases with transaction costs and limited participation both resulted with a doubling of global mitigation costs in 2020. Ensuring efficiency is, however, an issue of market design, but it might affect also effort sharing as the marginal costs are not necessarily equalized globally with inefficient markets.

Despite all these challenges, effort sharing is a necessity for the post-2012 climate policy. The negative costs for non-Annex I from the Triptych and Multistage, especially in the medium term, might provide a sufficient incentive for developing countries to accept binding targets. However, the gains are a result of wealth transfer from Annex I countries through allowance trading, the amount of which must be acceptable for Annex I countries. In this respect Triptych might provide a more balanced outcome of the two regimes assessed. It is yet good to bear in mind that the effort sharing will ultimately be a result of political negotiations. As said, there is no definitive answer to the equitable balance between costs and gains of different parties, but a quantified assessment of possible outcomes might aid the process considerably.

Acknowledgements

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Appendix A. Detailed results from effort sharing

Main quantitative results from effort sharing in the mitigation scenarios for each region is provided in Tables 2–5.

Appendix B. Supplementary data

Supplementary data associated with this article can be found in the online version at 10.1016/j.enpol.2009.11.055.

Table 2
Main outcomes of effort sharing with the 485 ppm-eq target in 2020—including GDP, baseline emissions, emissions after allowance trading, and allocations and mitigation costs with Triptych and Multistage effort sharing—with maximum and minimum values from the four baseline scenarios for each region.

	GDP (PPP) Bln. USD	Baseline emis. Gt CO_2−eq	Emissions Gt CO_2−eq	Triptych alloc. Gt CO_2−eq	Triptych cost Bln. USD	Multist. alloc. Gt CO_2−eq	Multist. cost Bln. USD
USA	15 000–16 000	7.9–8.4	6.6–7	5.1–5.7	21–48	4.4–4.9	32–66
W.Eur	14 000–15 000	4.7–5.1	3.7–4.2	2.9–3.2	14–33	3–3.3	13–32
FSU	3000–4100	3.4–3.9	2.8–3	2.3–2.5	5.8–17.4	2.6–2.8	1.2–15.0
E.Eur	1800–2600	0.88–0.99	0.72–0.79	0.73–0.78	0.4–2.3	0.89–0.95	−2.8–−0.6
Japan	4000–4500	1.3–1.4	1.1–1.1	0.86–0.94	2.4–4.5	0.89–1	0.7–3.6
Canada	1200–1400	0.75–0.79	0.59–0.64	0.37–0.41	4.4–8.2	0.36–0.4	4.5–8.5
Aus&NZ	820–920	0.74–0.74	0.57–0.62	0.52–0.56	2.2–3.7	0.34–0.38	5.0–8.4
China	12 000–17 000	6.6–7.3	5–5.4	6.8–7.7	−36–−11	6.2–7.2	−22–−2.7
L.Am	5300–6000	3–3.2	2.7–2.9	2.9–3.3	−4.4–9.7	2.3–2.8	2.2–19.8
Oth. Asia	5800–8100	3.2–3.9	2.8–3.3	3.4–3.7	−12.0–−7.4	3.6–3.9	−16–−11
Africa	4000–4800	3.2–3.4	2.8–2.9	2.9–3.2	−2.8–3.7	3–3.6	−12.0–1.6
India	5500–8500	2.9–3.6	2.2–2.5	2.7–3.1	−7.4–−3.1	3.8–4.5	−44–−19
M.East	3400–4000	2.8–3.2	2.5–2.8	2.3–2.5	12–58	2–2.3	14–65
Mexico	1700–1900	0.73–0.76	0.64–0.67	0.73–0.82	−1.4–0.8	0.57–0.7	0.4–3.3
S.Korea	1500–2100	0.74–1	0.59–0.75	0.56–0.62	−0.5–1.7	0.45–0.53	2.2–3.7

All values are on an annual basis, monetary values in USD2000.

Table 3
Main outcomes of effort sharing with the 550 ppm-eq target in 2020—including GDP, baseline emissions, emissions after allowance trading, and allocations and mitigation costs with Triptych and Multistage effort sharing—with maximum and minimum values from the four baseline scenarios for each region.

	GDP (PPP) Bln. USD	Baseline emis. Gt CO_2−eq	Emissions Gt CO_2−eq	Triptych alloc. Gt CO_2−eq	Triptych cost Bln. USD	Multist. alloc. Gt CO_2−eq	Multist. cost Bln. USD
USA	15 000–16 000	7.9–8.4	6.6–7	5.1–5.7	13–44	4.2–4.8	19–59
W.Eur	14 000–15 000	4.7–5.1	3.7–4.2	2.9–3.2	7–30	3–3.4	6–29
FSU	3000–4100	3.4–3.9	2.8–3	2.3–2.5	2.9–10.1	2.3–2.5	3.8–16.5
E.Eur	1800–2600	0.88–0.99	0.72–0.79	0.73–0.78	−0.5–1.1	0.78–0.83	−0.5–2.3
Japan	4000–4500	1.3–1.4	1.1–1.1	0.86–0.94	1.7–5.3	0.89–1	1.1–4.5
Canada	1200–1400	0.75–0.79	0.59–0.64	0.37–0.41	2.3–6.5	0.35–0.39	2.5–7.1
Aus&NZ	820–920	0.74–0.74	0.57–0.62	0.52–0.56	1.0–3.1	0.41–0.47	1.9–5.4
China	12 000–17 000	6.6–7.3	5–5.4	6.8–7.7	−29–−9	6.8–7.9	−21–−6.2
L.Am	5300–6000	3–3.2	2.7–2.9	2.9–3.3	−5.2–−0.9	3–3.7	−5.6–0.2
Oth. Asia	5800–8100	3.2–3.9	2.8–3.3	3.4–3.7	−15.6–−7.3	4.1–4.6	−22–−9
Africa	4000–4800	3.2–3.4	2.8–2.9	2.9–3.2	−5.4–−0.5	3.2–4	−12.3–−0.1
India	5500–8500	2.9–3.6	2.2–2.5	2.7–3.1	−11.7–−3.8	3.8–4.5	−30–−9
M.East	3400–4000	2.8–3.2	2.5–2.8	2.3–2.5	9–35	2.1–2.5	8–36
Mexico	1700–1900	0.73–0.76	0.64–0.67	0.73–0.82	−1.5–−0.7	0.72–0.88	−1.5–−0.2
S.Korea	1500–2100	0.74–1	0.59–0.75	0.56–0.62	−0.9–1.2	0.63–0.73	−1.0–0.6

All values are on an annual basis, monetary values in USD2000.

Table 4
Main outcomes of effort sharing with the 485 ppm-eq target in 2050—including GDP, baseline emissions, emissions after allowance trading, and allocations and mitigation costs with Triptych and Multistage effort sharing—with maximum and minimum values from the four baseline scenarios for each region.

	GDP (PPP) Bln. USD	Baseline emis. Gt CO_2−eq	Emissions Gt CO_2−eq	Triptych alloc. Gt CO_2−eq	Triptych cost Bln. USD	Multist. alloc. Gt CO_2−eq	Multist. cost Bln. USD
USA	22 000–30 000	8.8–11	2–2.4	0.56–0.63	1658–3052	0.39–0.56	1788–3094
W.Eur	18 000–27 000	5.2–6.4	1.1–1.4	0.58–0.66	787–1417	0.41–0.6	897–1450
FSU	6600–14 000	4.8–7.7	0.56–1.2	0.45–0.56	679–1819	0.34–0.44	774–1931
E.Eur	3100–6700	1.1–1.7	0.18–0.23	0.16–0.19	119–279	0.13–0.17	141–301
Japan	4900–6800	1.3–1.5	0.18–0.29	0.16–0.19	172–271	0.13–0.19	196–262
Canada	1800–2700	0.83–1.1	0.073–0.25	0.065–0.073	173–301	0.042–0.06	190–312
Aus&NZ	1100–1600	0.76–0.88	0.11–0.2	0.084–0.09	147–217	0.027–0.037	184–267
China	22 000–47 000	7.3–11	1.7–2.3	2.3–2.7	320–1005	1.6–1.9	822–1695
L.Am	12 000–18 000	4.8–6.5	1.3–1.6	1.3–1.6	672–1505	0.85–0.94	1057–1887
Oth. Asia	13 000–28 000	4.9–8.7	1.5–2.3	2.3–2.4	56–1107	2.4–2.7	−170–771
Africa	12 000–22 000	6.4–8.5	2–2.3	2.9–3.3	−260–453	3.2–4	−545–25
India	14 000–38 000	4.5–8.6	1.1–1.3	2.3–2.6	−455–−208	3.2–4.8	−2767–−778
M.East	8500–15 000	5.4–8.8	1.1–1.6	0.92–1.1	892–2349	0.54–0.76	1197–2696
Mexico	3900–6200	1.2–1.6	0.29–0.34	0.33–0.35	136–315	0.18–0.2	236–453
S.Korea	2800–5900	0.95–2.1	0.11–0.32	0.11–0.13	153–524	0.06–0.069	176–587

All values are on an annual basis, monetary values in USD2000.

Table 5
Main outcomes of effort sharing with the 550 ppm-eq target in 2050—including GDP, baseline emissions, emissions after allowance trading, and allocations and mitigation costs with Triptych and Multistage effort sharing—with maximum and minimum values from the four baseline scenarios for each region.

	GDP (PPP) Bln. USD	Baseline emis. Gt CO_2−eq	Emissions Gt CO_2−eq	Triptych alloc. Gt CO_2−eq	Triptych cost Bln. USD	Multist. alloc. Gt CO_2−eq	Multist. cost Bln. USD
USA	22 000–30 000	8.8–11	3.4–3.7	1.2–1.4	595–1721	0.9–1.1	699–1769
W.Eur	18 000–27 000	5.2–6.4	1.8–2	1.1–1.2	281–780	1.1–1.2	305–719
FSU	6600–14 000	4.8–7.7	1.8–2.1	0.87–1.1	278–1009	0.7–0.76	335–1179
E.Eur	3100–6700	1.1–1.7	0.35–0.38	0.37–0.4	26–107	0.26–0.3	47–161
Japan	4900–6800	1.3–1.5	0.37–0.48	0.29–0.31	70–154	0.32–0.37	68–113
Canada	1800–2700	0.83–1.1	0.36–0.39	0.15–0.19	61–153	0.1–0.11	79–175
Aus&NZ	1100–1600	0.76–0.88	0.25–0.38	0.17–0.21	44–118	0.091–0.1	67–156
China	22 000–47 000	7.3–11	3.1–3.7	4.5–5	−180–−44	3.7–4.8	−66–514
L.Am	12 000–18 000	4.8–6.5	2.5–3	2.3–3	110–708	2–2.3	245–887
Oth. Asia	13 000–28 000	4.9–8.7	2.6–3.4	3.7–4	−108–260	4–4.3	−212–73
Africa	12 000–22 000	6.4–8.5	3.4–3.5	4–4.8	−215–144	5–5.6	−655–−201
India	14 000–38 000	4.5–8.6	1.9–2.2	3.7–4.6	−649–−213	5.2–6.2	−1278–−524
M.East	8500–15 000	5.4–8.8	2.3–2.9	1.6–2.1	445–1426	1.1–1.4	572–1761
Mexico	3900–6200	1.2–1.6	0.49–0.63	0.65–0.71	22–129	0.47–0.55	54–223
S.Korea	2800–5900	0.95–2.1	0.35–0.54	0.26–0.4	49–241	0.17–0.2	60–348

All values are on an annual basis, monetary values in USD2000.

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