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Differentiating commitments world wide: global differentiation of GHG emissions reductions based on the Triptych approach—a preliminary assessment

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Abstract

In the context of global climate negotiations various approaches have been proposed to distribute commitments regarding greenhouse gas emissions mitigation over different countries. One of them is the Triptych approach, which is a sector approach that accounts for differences in national circumstances such as population size and growth, standard of living, economic structure and fuel mix in power generation. It was successfully applied in the negotiations on differentiation of commitments in the European Union in 1997.

In this study we aim to see what problems we encounter when applying the approach in a wider geographical context. In order to reach this aim we establish a test differentiation of CO_2 emission reduction obligations for a selection of 48 countries. The criteria we apply comprise technical emission reduction options only. According to our Triptych criteria, including the choice for particular growth scenarios and a convergence of CO_2 emissions in the domestic sectors by the year 2030, the sum of CO_2 emissions in the 48 countries in 2015 is estimated to increase by 8% over 1990 levels. With the criteria used the average reduction objective for the OECD will be somewhere between −10% and −20%. For economies in transition to a market economy our calculations indicate on average a reduction between −30% and −50%. For the developing countries we established increases varying roughly from +40% to +200%.

The choice for a particular growth scenario as well as the assumption for the period for the convergence of per capita emissions in the domestic sectors are crucial and may effect the outcome of the calculations to a large extent. If these problems can be sufficiently solved the Triptych approach can serve as a valuable tool to rank countries in a global differentiation scheme. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Differentiation of commitments; National circumstances; Triptych approach

1. Introduction

In the context of global climate negotiations various approaches have been proposed to distribute commitments with respect to climate mitigation over different countries. A large number of possible differentiation rules have been proposed so far (Grubb et al., 1992; Kinley and Terrill, 1996). Among these are equal per capita emissions rights, reductions based on current energy use or current emissions per capita or per unit of GDP, GDP per capita, GDP growth, share in global emissions, etc. In spite of the wide range of possible indicators, none turned out to constitute a widely acceptable differentiation rule. The variety of national circumstances that one would like to consider is generally too wide to capture in one single indicator. Therefore, simple differentiation rules are too crude to be used as a suitable discriminating rule. More complex differentiation schemes that have been proposed are based on marginal costs of abatement or past contributions to climate change. However, a large data set is required to calculate marginal cost of abatement properly. The enormous data requirement is a major drawback of such an approach to differentiation of commitments.

An alternative approach to differentiation of commitments has been proposed by Phylipsen et al. (1998b), who developed the Triptych approach. It has been applied to

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the Member States of the European Union and it has proven its usefulness in the period preceding the climate negotiations in Kyoto, 1997. The countries in the European Union opted for a joint fulfilment of their reduction obligations under the UNFCCC, to be specified in the Kyoto Protocol. However, initially efforts to reach agreement on a joint negotiating position indicated that it was necessary to negotiate a total European Union wide abatement target and individual national targets simultaneously. Both were set at the European Union Ministerial Environment Council of March 1997 (EU Environment Council, 1997) in which the Triptych approach played an important role. It increased mutual understanding of reasonable contributions to an overall reduction objective for each of the Member States by taking into account national circumstances, such as population size and growth, standard of living, economic structure and fuel mix in power generation (Ringius, 1999).

Considering the contribution of the Triptych approach in the context of the European Union, the question arises if it could offer useful assistance in global climate negotiations as well. The outcome of the Kyoto negotiations in 1997 already showed that the Parties to the UNFCCC basically agree on the principle of differentiated commitments. It would be desirable however if the political negotiations on differentiated targets could be supported by more scientific insights with respect to a reasonable ranking order of countries in a differentiation scheme. This article aims to contribute to such insights by testing the applicability of the Triptych approach in a world wide context.

Our differentiation calculations include CO_2 emissions only. We will determine national emission reduction objectives for the year 2015 applying roughly the same criteria in the three sectors as Phylipsen et al. (1998b) did in their study for the European Union (Table 8). For two reasons we adjusted the criteria slightly. The first reason is that we will apply the criteria to a wider variety of countries, not only geographically but also, e.g. regarding their levels of development, energy efficiencies or fuel mixes in power generation. Therefore more differentiation is necessary, although at the same time a wider range of countries hampers a far too refined approach. For instance we will differentiate economic growth rates for as many as 11 world regions, but detailed information on national policies regarding fuel mix in power generation (as has been incorporated in European Union Triptych calculations) will not be taken into account. Second, we want to improve the Triptych approach as applied to the European Union. We will account for structural changes within the energy-intensive energy by applying different growth rates for the various industrial subsectors. Another improvement is the assumption that generation efficiencies in the power-producing sector increase substantially and converge on the long term.

We will not adjust the criteria so as to find the same overall reduction as Phylipsen did. We intend to let the total reduction in CO_2 emissions result from the criteria applied, not the other way around because we want to compare our results with the results from Phylipsen et al. For our calculations we will assume growth rates for the economy and physical production that were taken from intermediate scenarios that we will discuss later. The criteria we will apply do not imply a restriction of growth represent technical measures only. CO_2 reduction due to decreased activity may occur as mitigation strategies might involve a decreased growth of the economy, but we consider this a second-order effect that we will not take into account beforehand.

In the following we will first explain our selection of countries for this study. Next, we will present the Triptych approach and specify the criteria that we used to calculate a differentiation of commitments. We present a differentiation scheme that results from these criteria. The article ends with a discussion and a number of relevant conclusions.

2. Geographical scope

In our selection of countries to include in our Triptych calculations on differentiation of commitments we chose to include the 25 countries with the highest total CO_2 emissions. We added the 10 countries with the highest growth in CO_2 emissions provided that they are also in the top 50 of total CO_2 emissions. We extended the selection to include all Annex I countries, which are the countries that have committed themselves to a quantitative CO_2 target. Luxembourg and Monaco were omitted because of their small size. We left out Uzbekistan and Croatia because of data quality issues. We also excluded India and Indonesia. As both are low-income countries it is unlikely that they will accept quantitative reduction obligations within a few decades. Although quantitative reduction obligations for developing countries are being debated strongly and although there are countries within the G77 opposing it, we did include them in our calculations. At the fourth Conference of the Parties in Buenos Aires Argentina already demonstrated its willingness to accept voluntary commitments under the UN Framework Convention on Climate Change. In addition our method is capable of establishing growth percentages rather than reduction rates for developing countries which might make quantitative commitments more accessible for these countries. The inclusion of developing countries might help to shed light on shortcomings and a possible northern bias of our method. In future studies we might for instance adjust the Triptych approach in such a way that it helps to establish reasonable decarbonisation objectives rather than quantitative commitments. Although the US are not very keen on ratifying the Kyoto Protocol we did include them in our differentiation calculations too. The purpose of our calculations is not to present a ready-made outcome of future climate negotiations, but rather to provide the negotiating parties with insight into how they can be ranked in their possibilities to reduce emissions. Such insights increase the quality of the negotiation process, whatever the outcome may be. In total our selection included 48 countries, plus the European Union, which together accounted for 86% of the global CO_2 emissions from fuel combustion in 1995. Table 1 lists the selected countries and their total CO_2 emissions from fuel combustion, past mean annual growth in CO_2 emissions, CO_2 emissions per GDP and CO_2 emissions per capita. It is obvious that a wide range in emissions exist. CO_2 emissions per capita vary from 1.8 to 19.9 t for Brazil and the US, respectively. CO_2 emissions per unit GDP vary from 0.33 to 3.51 kg/1990 US$ for Brazil and Kazakhstan, respectively.

3. The Triptych approach

The Triptych approach is a sector approach distinguishing three categories of emissions, corresponding to three groups of economic sectors: the energy-intensive industry, the power producing sector and the domestic sectors. Accounting for varying national circumstances different criteria are used for each of the three categories to calculate sectoral allowances. The allowances for each sector add up to a proposed national allowance for each country. The Triptych approach offers a sectoral analysis *only as a tool* to determine a national allowance. There is no intention to establish sectoral commitments, agreed on either at the national level or at the level of economic sectors, as this would hamper countries in their flexibility to pursue cost-effective emissions reduction strategies.

In the following we will first discuss the scenarios that we included in the calculation and next the criteria we applied to calculate a global differentiation of commitments. The formulae we applied are given in Appendix A. As indicated briefly in Section 1, our criteria deviate slightly from the criteria Phylipsen et al. used as will be discussed in the discussion.

3.1. Scenarios

In our calculations we used scenarios from three different sources that we consider consistent. No scenario was available that provides all the data that we require for our analysis. We took population forecasts from the United Nations (UNDP, 1999). Economic forecasts come from a joint study from the World Energy Council and the International Institute for Applied System Analysis (WEC and IIASA, 1998). Prognoses for physical production growth in heavy industry were taken from a World Energy Council study (WEC, 1995). The WEC/IIASA scenarios (1998) and the WEC scenarios (1995) both elaborate three scenarios that had been presented in an earlier WEC study (1993).

The economic forecast is from a middle course scenario (WEC and IIASA, 1998) which corresponds to case B in the earlier WEC study aforementioned (WEC, 1993), and contrary to the latter also explores the future beyond 2020. This middle course scenario is characterised by a modest economic growth and technological development, the disappearance of trade barriers and increasing international exchange. Population growth is the same as in the earlier WEC study (1993) and stems from the UN Base Case scenario.

The scenario for the growth of the physical production has been taken from WEC (1995). This WEC study describes three different scenarios with respect to energy-efficiency improvements and also elaborates the three scenarios presented in the 1993 study from the World Energy Council. The scenarios differ with respect to the energy intensity of the economy, but they all assume the same population growth, based on the UN Base Case scenario and the same growth in physical production.

All scenarios represent a middle course future and have comparable story lines. In spite of the different time horizons (2100, 2050 and 2020, respectively) the combination of the three seems to form a suitable basis for our analysis.

3.2. The energy-intensive industry

The internationally oriented energy-intensive industry, further indicated as heavy industry, has relatively high CO_2 emissions per unit of production. Consequently, countries that rely to a large extent on this sector have higher CO_2 emissions than countries that are more dependent on services, light industry or agriculture. The international character of this sector means that countries lacking sizeable heavy industries import goods from heavy industry in other countries and thus profit from other countries' efforts in this sector. Countries should not necessarily be penalised for an energy-intensive industry as they supply goods consumed by other countries.

The energy-intensive industry in this study comprises the following subsectors: iron and steel, the chemicals, pulp and paper, non-metallic minerals, non-ferrous metals and the energy transformation sector, including petroleum refining, the manufacture of solid fuels, coal mining, oil and gas extraction and any energy transformation other than power production. The criteria and assumptions that we will apply for heavy industry are summed up hereafter.

- Growth rates in physical production are according to a report of the World Energy Council (WEC, 1995)

Table 1
Selected countries with 1995 total CO_2 emissions from fuel combustion, mean annual growth in CO_2 emissions, CO_2 emissions per GDP and CO_2 emissions per capita (IEA, 1997a)

	Annex I/OECD	Total CO_2 emissions (Mt)	Mean annual growth CO_2 emissions (%)	CO_2 emissions per GDP[a] (kg CO_2/1990 US$)	CO_2 emissions per capita[b] (t)
		1995	1985–1995[c]	1995	1995
Argentina		128	2.9	0.55	3.7
Australia	A1/O	286	2.5	0.90	15.8
Austria	A1/O	60	0.6	0.42	7.5
Belgium	A1/O	117	1.1	0.65	11.6
Brazil		287	3.9	0.33	1.8
Bulgaria	A1	57	− 4.0	1.89	6.8
Canada	A1/O	471	1.5	0.84	15.9
China		3007	4.9	0.92	2.5
Chinese Taipei		167	8.6	0.50	7.8
Czech	A1/O	120	− 3.4	1.50	11.7
Denmark	A1/O	61	− 0.4	0.60	11.6
Estonia	A1	20	− 9.1	2.56	13.4
European Union	A1/O	3180	0.1	0.51	8.6
Finland	A1/O	54	0.5	0.68	10.7
France	A1/O	362	− 0.7	0.34	6.2
Germany	A1/O	884	− 1.5	0.63	10.8
Greece	A1/O	77	2.6	0.70	7.3
Hungary	A1/O	58	− 3.1	0.93	5.6
Iceland	A1/O	2	2.5	0.48	8.8
Iran		233	4.3	3.03	3.6
Ireland	A1/O	35	2.2	0.66	9.7
Italy	A1/O	424	1.6	0.42	7.4
Japan	A1/O	1151	2.4	0.46	9.2
Kazakhstan		186	− 11.3	3.51	11.2
Latvia	A1	10	− 15.3	0.99	3.8
Lithuania	A1	15	− 10.2	1.25	4.2
Malaysia		92	8.3	0.56	4.6
Mexico	O	328	1.6	0.51	3.5
The Netherlands	A1/O	179	1.8	0.65	11.6
Norway	A1/O	34	1.5	0.37	7.8
New Zealand	A1/O	29	2.6	0.55	8.2
Poland	A1/O	336	− 3.1	1.57	8.7
Portugal	A1	51	6.6	0.45	5.1
Romania	A1	124	− 3.6	1.69	5.5
Russia	A1	1548	− 7.8	2.24	10.4
Saudi Arabia		227	4.6	1.32	12.0
Singapore		59	13.4	0.75	19.7
Slovakia	A1	40	− 4.1	1.35	7.5
Slovenia	A1	13	− 0.2	na	6.7
South Africa		321	0.9	1.86	7.7
South Korea	O	353	10.7	0.70	7.9
Spain	A1/O	247	2.6	0.49	6.3
Sweden	A1/O	56	− 1.0	0.36	6.4
Switzerland	A1/O	42	0.1	0.29	5.9
Thailand		156	13.1	0.41	2.7
Turkey	A1/O	161	4.9	0.41	2.6
United Kingdom	A1/O	565	− 0.1	0.57	9.6
Ukraine	A1	431	− 10.6	2.88	8.4
United States	A1/O	5229	1.2	0.85	19.9

[a]Based on Purchasing Power Parity.
[b]1992–1995 for Estonia, Latvia, Lithuania, Kazakhstan, Russia, Ukraine.
[c]All sectors, i.e. including heavy industry and the power-producing sector.

Table 2
Annual growth rates (1990–2020) for physical production in five subsectors of the energy-intensive industry for the OECD, Eastern Europe and the Former Soviet Union (EE/FSU) and developing countries, respectively. Figures regard a business-as-usual scenario (WEC, 1995)

	OECD (%)	EE/FSU (%)	Developing countries (%)
Iron and Steel	0.70	0.10	4.00
Chemicals[a]	1.76	0.98	4.11
Petroleum refineries	1.00	1.00	3.00
Pulp & Paper	1.50	1.50	5.50
Cement	1.00	1.00	4.00

[a]The WEC report gives separated growth figures for various chemical products. The aggregated figure for the entire chemical industry was not included in the report itself and taken from the authors' spreadsheet.

and are given in Table 2. These growth figures represent business-as-usual circumstances and are specified for three regions and five subsectors of the energy-intensive industry. We assume growth rates in the entire non-metallic minerals sector equal to those in the cement sector. Growth rates in the non-ferrous metals industry are assumed equal to those in the iron and steel industry. In our calculation of partial allowances in heavy industry we assign the OECD members Korea, Turkey and Mexico the same growth rates in physical production as developing countries. Poland is assigned the same growth rate as an economy in transition.

- All countries reduce their specific CO_2 emission (CO_2 emissions[1] per unit of physical product) by 1.5%/yr. In the present study we will not take into account differences in energy efficiency as yet. Phylipsen et al. (1997) considered an energy-efficiency improvement of 1.5–2.0% feasible although stimulating policies are required.

The criteria in heavy industry criteria do not differ very much from the criteria Phylipsen et al. used in their study for the European Union. However we choose to use differentiated growth rates, whereas Phylipsen et al. used uniform growth rates for all countries and subsectors. The differentiated growth rates for the three regions represent a certain convergence within the heavy industry sector. The reason for the differentiation of growth rates in the various subsectors is that this will enable us to account for structural changes within the economy.

3.3. *The power-producing sector*

We distinguish the power-producing sector because specific CO_2 emissions from power production vary to a large extent, due to large differences in the share of nuclear power and renewables and in the fuel mix in fossil-fuel-fired power plants. The potential for cutting CO_2 emissions from this sector differs accordingly. Therefore fuel mix in power generation is an important national circumstance to account for in a differentiation of commitments. In our calculations on the power sector we will not include autoproducers existing in 1990 in our analysis. We consider these existing power generation units in industry as part of the fleet of machinery in the energy-intensive industry that will be subject to an improvement rate of the specific CO_2 emission (see above).

Our criteria and assumptions for the power-producing sector are the following:

- Growth rates in power production equal economic growth rates minus an annual reduction by 1% to correct for the reduced demand due to efficiency improvements. The economic growth rates are from the study from the 'middle course' scenario from the World Energy Council and the International Institute for Applied System Analysis (WEC and IIASA, 1998). They are mentioned in Table 3 for eleven regions separately.[2]
- All countries reduce their electricity output generated with solid and liquid fossil fuels by 30% each.[3,4] Considering a 30-yr lifetime of fossil-fuel-based capacity, a phasing out of 30% of the capacity in the years until

[1] CO_2 emissions from heavy industry and the domestic sectors in the year 1990 were taken from IEA statistics (IEA, 1997a).

[2] In the power-producing sector Phylipsen et al. made a distinction between poorer (i.e. Cohesion Fund—Greece, Ireland, Portugal, Spain) and richer countries in the European Union. Their growth assumption for non-Cohesion Fund countries was smaller than the growth rate we have assumed (0.9% vs. 1.9%). As our scope is wider, both geographically and with respect to the development level, we choose not to differentiate growth within the EU. Instead we distinguish 11 world regions for which we do differentiate growth.

[3] For this output we take the sum of regular and CHP power generation output in 1990, except for Bulgaria (1991), Estonia, Latvia, Lithuania, Romania, Ukraine (1992), Croatia and Russia (1993).

[4] In this study we exclude national policies. We do not include the foreseen much stronger cuts in solids fossil fuels in Denmark, Germany and the United Kingdom as Phylipsen et al. did, by setting more stringent reduction of solids fossil fuels for these countries.

Table 3
Annual economic growth rates (1990–2050) for eleven regions.

North America	2.0%
Western Europe	1.9%
Pacific OECD	1.5%
Central and Eastern Europe	0.9%[a]
Former Soviet Union	0.7%[b]
Centrally Planned Asia & China	5.0%
South Asia	3.6%
Other Pacific Asia	4.4%
Middle East & North Africa	3.3%
Sub-Saharan Africa	3.0%
Latin America & the Caribbean	3.0%
World	2.2%

[a] Including economic collapse in the years before 1991. The corresponding growth figure for 1991 onwards is 1.2% (excluding countries in former Yugoslavia, which we do not include in this study) (Worldbank, 1999).

[b] Including economic collapse in the years before 1994. The corresponding growth figure for 1994 onwards is 2.8% (excluding Uzbekistan, which we do not include in this study) (Worldbank, 1999).

2015 seems achievable taking into account regular turn-over of capital stock and provided that national policies are directed towards less carbon-intensive forms of power production.

- The 2015 share of the output from nuclear power capacity equals the share in 1990. Nuclear power is a sensitive issue and it seems preferable to take national preferences into account. We assume that these are reflected by the current share that nuclear power has in electricity output. Of course nuclear policies may be altered in the years until 2015 but is practically impossible to take these changes into account beforehand.
- Renewables have an additional 8% share of the 2015 electricity production on top of their 1990 output. Countries may have very different potentials for various options of renewable energy. Nevertheless it appears that studies on these potentials are hardly ever consistent in their assumptions and that results are not comparable (Hoogwijk et al., 2000). In addition, renewable energy trading schemes, possibly connected to the flexible mechanisms agreed on in the Kyoto Protocol may be used to implement renewable energy projects abroad, which leads to an equalisation of costs of renewable energy among countries.
- Combined Heat and Power produces an additional 15% of the electricity in 2015 (unless remaining solid and liquid fossil fuels, nuclear energy and renewables already fully cover a country's electricity output). The 1990 CHP capacity is included in the output from regular generation. For Combined Heat and Power generation we assumed 70% as the 'shadow efficiency' for electricity generation in 2015 (Appendix C). CHP is assumed to be fired with natural gas.

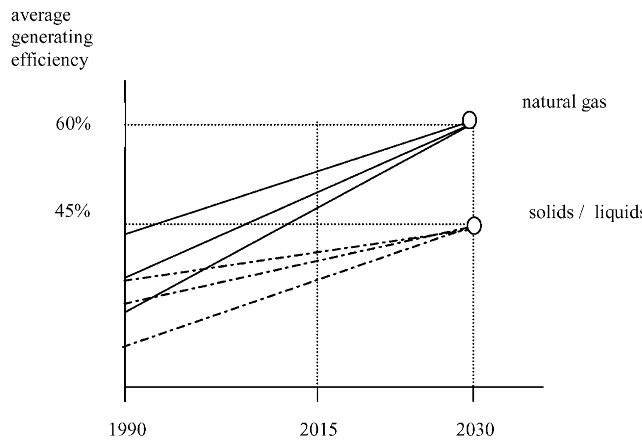

Fig. 1. Convergence levels for average generating efficiencies in 2030 (small circles) and the hence foreseen generating efficiencies from 1990 onwards for both gas and solid and liquid fossil fuels in three arbitrary countries.

- The remaining electricity is produced with natural gas.[5,6]
- Average generating efficiencies for solid, liquid and gaseous fossil fuels converge. The replacement by new capacity will gradually lead to a similar level of efficiency in all countries as the market for generation capacities has a global character. At present the state-of-the-art conversion efficiency for natural gas-fired power generation is 58% and approaching 60% on a lower heating value basis (Smith, 1999). For solid and liquid fuels these values are well over 45% now (Anonymous, 1995). Taking into account a typical lifetime of 30 years for power plants, which corresponds to regular turnover rates, such values could be reached in 2030.[7] We will assume a linear convergence to a level of 60% for natural gas-fired power plants and to 45% for power plants on liquid and solid fuels. Fig. 1 depicts the convergence for three arbitrary countries and different fossil fuels.

Some countries in 1990 lacked natural gas-based generating capacity and for others satisfactory data were

[5] Emission factors for the various fossil fuels were taken from the IPCC (IPCC, 1995): hardcoal 25.8 kg C/GJ (value for coking and other butiminous coal), brown coal 27.6 (value lignite), peat 28.9 (distinguished for OECD only), liquid fossil fuels 20.0 and natural gas 15.3 kg C/GJ.

[6] CO_2 emissions are taken from (IEA, 1997a). They regard 1990 levels except for Bulgaria (1991), Estonia, Latvia, Lithuania, Kazakhstan, Ukraine (1992) and Russia (1993). US emissions for heavy industry in 1990 were calculated from (IEA, 1997b). For the year 2015 all emissions will be calculated on the base of the energy consumption data that were derived using the criteria mentioned in the text.

[7] Of course conversion efficiencies are likely to increase further beyond present state-of-the-art values. On the other hand actual conversion efficiencies will be lower than the name plate efficiencies we mention in the text.

not available. For these countries we assume that in 2015 the average efficiency equals 50% efficiency for gas based capacity.

Appendix B shows the 1990 generating efficiencies for solids, liquids and gas.

3.4. The domestic sectors

The domestic sectors comprise various sectors: apart from the residential sector (households), also the commercial sector, transportation, light industry and agriculture are included in this category. Emissions in these sectors are assumed to be correlated with population size, as they are determined by the number of people that live in dwellings, have a workplace, transport themselves, etc. Our criteria and assumptions comprise:

- Population grows as forecasted by the United Nations (UNDP, 1999).[8]
- 1990 per capita emission levels for the various countries converge to equal per capita allowances for all in 2030. In this way it takes into account differences in the standard of living that we assume to be reduced in the future (Fig. 2).
- The convergence level was set at 3.44 t CO_2 per capita (0.94 tC/capita). This figure was derived from Phylipsen et al. They considered a 15% reduction of the 1990 average per capita emission by the year 2010 within the European Union reasonable arguing that this level can be achieved with efficiency measures only, while the current development in standard of living within the European Union can be maintained.[9] According to their data this 15% reduction in the domestic sectors corresponds to 2.96 t CO_2/capita in 2030. However domestic emissions derived from IEA statistics are higher than the domestic emissions used by Phylipsen et al. In order to correct for this we adjusted the convergence level upward to 3.44 t CO_2/capita.[10,11] Current per capita CO_2 emissions for major world regions are mentioned in Table 4.

Table 4
CO_2 emissions {t/c} per capita in the domestic sectors in 1990, derived from IEA (IEA, 1997a)

Annex I	6.3
USA and Canada	11.0
European Union[a]	4.9
Economies in transition to a market economy[b]	5.6
Non-Annex I[c]	1.2

[a] Excluding Luxembourg.
[b] Bulgaria, Czech Republic, Estonia, Hungary, Kazakhstan, Latvia, Lithuania, Poland, Romania, Russia, Slovakia, Ukraine.
[c] Non-Annex I included in this study only.

4. A global differentiation of commitments based on the Triptych approach

In this section we will discuss partial allowances and overall national allowances that result from the Triptych calculations. Table 5 gives partial allowances in the power-producing sector and an overview of fuel mixes for power generation in 1990 and 2015 that may help to understand these partial allowances. Fuel mixes were based on the electricity output (GWh) generated by the various sources. Table 6 presents the partial allowances of all three sectors as well as overall national reduction targets. Note that the results indicate in a normative way how future reduction obligations might be distributed. They do not represent a scenario that can be extended to the remote future.

4.1. The energy-intensive industry

Emission reduction figures in heavy industry (Table 6) are determined by growth rates for the individual subsectors and the relative size of the subsectors. Growth rates turn out to be decisive for the partial allowances in this sector. All developing countries have high partial allowances here: 50% or more above the preset level. Countries in the former Soviet Union (FSU) and Eastern Europe (EE) on the contrary will have to reduce their emissions in heavy industry by 10% or more according to our Triptych criteria.

In general, absolute reductions in the energy intensive industry are not as large as in the other sectors. For a limited number of countries however absolute reductions in heavy industry are substantial because of its size and its large reductions, such as for Chinese Taipei, South Korea, Singapore, South Africa, Mexico and China.

4.2. The power-producing sector

The criteria defined for the power sector previously result in vastly varying partial reduction objectives, depending on the composition of the 1990 fuel mix. These

[8] Except Chinese Taipei, which is not recognised by the UN. Here the current population figure was taken from the Taiwanes Hakka Association of USA (Taiwanese Hakka Association of USA, 1999). We assume growth equal to China's population growth rate.

[9] This figure was based on work of the European Union Expert Group on Climate (Phylipsen et al., 1997).

[10] We base the correction factor on a comparison of the IEA data on per capita emissions in the domestic sectors within the European Union with the Capros data (Capros et al., 1995) used by Phylipsen et al. (1998b).

[11] The most important difference with the criteria from Phylipsen et al. (1998b) is the omission of a climate correction in the present study. The reason for this is that for most countries we have no data on degree-days available as yet. For 14 Countries in the European Union we will check the influence of climate though (see discussion).

Table 5

CO_2 emissions for the power-producing sector in 1990, 2015 emissions without shifts in fuel mix (business-as-usual or BaU) and with changes in fuel mix according to Triptych (TT) criteria, respectively, partial allowances relative to 1990 and fuel mixes for 1990 and 2015

	CO_2 emissions				1990 share in output (GWh)					2015 share in output[a] (GWh)					
	1990	2015 BaU	2015 TT criteria	Part. allow relative to 90 (%)	Solids (incl. peat)[b] (%)	Liquids[b] (%)	Gas[b] (%)	Nuclear (%)	Renewables (incl. bio-mass) (%)	Solids (incl. peat) (%)	Liquids (l%)	Gas (%)	Nuclear (%)	Renewables (incl. bio-mass) (%)	Additional CHP[c] (%)
Argentina	15	25	15	2	1	10	32	17	41	0	4	31	17	33	15
Australia	125	141	87	− 30	80	1	9	0	10	49	1	18	0	17	15
Austria	10	12	9	− 6	14	3	13	0	69	8	2	12	0	64	15
Belgium	20	24	13	− 34	24	1	10	63	2	14	1	0	63	10	14
Brazil	6	10	45	658	1	1	0	1	97	1	0	16	1	67	15
Bulgaria	28	27	12	− 56	50	1	6	37	7	36	1	0	37	15	12
Canada	96	122	83	− 14	19	3	1	17	60	10	2	1	17	55	15
China	596	1569	666	12	72	7	1	0	20	19	2	48	0	16	15
Chinese Taipei	36	94	52	47	25	25	1	38	10	7	7	21	38	12	15
Czech	45	44	31	− 32	71	5	2	20	2	51	3	0	20	10	15
Denmark	23	28	17	− 24	92	3	2	0	3	52	2	22	0	10	15
Estonia	17	16	8	− 51	91	4	5	0	0	65	3	9	0	8	15
European Union	875	1089	630	− 28	36	8	6	37	13	20	5	5	37	19	15
Finland	15	18	9	− 36	26	1	7	42	24	14	1	1	42	27	15
France	22	28	14	− 38	5	1	0	79	14	3	1	0	79	19	0
Germany	311	388	203	− 35	56	1	6	32	4	32	1	9	32	12	15
Greece	34	43	24	− 29	74	20	0	0	6	41	11	19	0	13	15
Hungary	16	16	7	− 54	30	4	16	50	1	21	3	2	50	9	15
Iceland	0	0	0	4659[d]	0	0	0	0	100	0	0	0	0	88	12
Iran	31	55	35	10	0	32	56	0	11	0	13	58	0	14	15
Ireland	11	14	8	− 24	56	10	27	0	7	32	6	34	0	14	15
Italy	108	134	94	− 13	17	49	17	0	17	9	28	26	0	22	15
Japan	291	328	224	− 23	10	27	25	27	12	6	17	17	27	19	15
Kazakhstan	115	108	49	− 57	72	9	11	0	8	54	7	7	0	17	15
Latvia	0	0	0	23	0	8	25	0	67	0	6	0	0	80	14
Lithuania	5	4	1	− 75	0	15	5	78	2	0	11	0	78	10	1
Malaysia	15	34	20	33	13	42	26	0	18	4	13	52	0	16	15
Mexico	64	105	67	5	7	54	11	3	25	3	23	33	3	23	15

The Netherlands	37	46	31	− 15	42	0	52	6	0	23	0	47	6	8	15
Norway	0	0	5	6658	0	0	0	0	100	0	0	0	0	88	12
New Zealand	4	4	2	− 31	1	0	18	0	81	1	0	4	0	80	15
Poland	141	137	84	− 40	97	0	0	0	3	70	0	4	0	11	15
Portugal	14	18	12	− 15	33	32	0	0	34	19	18	13	0	36	15
Romania	51	50	21	− 59	35	8	35	0	22	25	6	23	0	31	15
Russia	850	792	249	− 71	13	9	43	13	21	10	7	24	13	31	15
Saudi Arabia	37	64	43	17	0	61	39	0	0	0	25	52	0	8	15
Singapore	13	31	17	25	0	100	0	0	0	0	31	46	0	8	15
Slovakia	8	8	5	− 39	32	3	5	51	8	23	2	0	51	16	7
Slovenia	4	4	2	− 47	33	0	1	41	25	24	0	0	41	34	1
South Africa	136	221	127	− 7	94	0	0	5	1	40	0	31	5	8	15
South Korea	38	87	45	19	19	18	9	49	6	6	5	14	49	11	15
Spain	62	77	47	− 25	40	5	1	37	17	23	3	1	37	22	15
Sweden	4	4	2	− 32	1	0	1	49	49	1	0	0	49	48	3
Switzerland	1	1	1	17	0	0	0	46	54	0	0	0	46	51	3
Thailand	32	73	42	32	25	23	40	0	11	8	7	57	0	13	15
Turkey	27	33	21	− 21	37	2	19	0	43	21	1	21	0	42	15
UK	205	255	160	− 22	67	10	0	21	2	38	6	11	21	10	15
Ukraine	146	136	76	− 48	26	10	31	30	3	19	8	17	30	12	15
US	1887	2408	1444	− 23	56	4	9	21	10	31	2	16	21	16	15

[a] Note that the shares of the various sources add up to slightly over 100% for France, Lithuania and Slovenia.

[b] Including fossil fuel input in Combined Heat and Power plants.

[c] This is on top of CHP already present in 1990. The 1990 contribution in most countries is not given in this table as it generally was counted under 'autoproducers'.

[d] The extremely low-emission figure in 1990 resulted in an extraordinarily high growth percentage.

Table 6
1990 share in CO_2 emissions, 1990 and 2015 CO_2 emissions and partial reduction objectives in heavy industry, the power-producing sector and the domestic sectors; total 1990 and 2015 CO_2 emissions and national reduction objectives

	Heavy industry				Power generation				Domestic sectors					Total		
	Share 1990 (%)	1990	2015	Reduction (%)	Share 1990 (%)	1990	2015	Reduction (%)	Share 1990 %	1990	2015	Reduction (%)	Red p/c (%)	1990	2015	Reduction (%)
Argentina	14	13	20	53	16	15	15	2	71	69	128	86	39	97	164	68
Australia	17	46	41	– 12	47	125	87	– 30	36	96	94	– 2	– 25	267	222	– 17
Austria	20	12	10	– 11	17	10	9	– 6	64	37	34	– 11	– 18	59	53	– 10
Belgium	27	29	26	– 11	18	20	13	– 34	55	59	45	– 23	– 26	107	84	– 22
Brazil	30	66	119	81	3	6	45	658	67	147	503	243	154	218	667	205
Bulgaria	16	9	8	– 18	47	28	12	– 56	38	22	24	8	21	59	44	– 26
Canada	20	87	80	– 8	22	96	83	– 14	58	249	188	– 24	– 39	432	352	– 19
China	35	837	1565	87	25	596	666	12	40	940	3457	268	201	2373	5688	140
Chinese Taipei	40	46	86	86	31	36	52	47	29	33	69	108	71	115	207	80
Czech Republic	19	28	24	– 12	30	45	31	– 32	51	77	49	– 36	– 34	150	104	– 30
Denmark	8	4	4	– 8	43	23	17	– 24	50	26	22	– 18	– 21	53	43	– 20
Estonia	3	1	1	– 10	63	17	8	– 51	33	9	6	– 35	– 22	26	15	– 44
European Union	18	568	523	– 8	27	875	630	– 28	55	1761	1445	– 18	– 19	3204	2598	– 19
Finland	25	14	13	– 8	27	15	9	– 36	48	27	22	– 18	– 22	55	44	– 20
France	20	75	68	– 8	6	22	14	– 38	74	279	240	– 14	– 19	376	322	– 14
Germany	16	154	142	– 7	32	311	203	– 35	53	517	377	– 27	– 30	982	722	– 26
Greece	13	9	8	– 11	47	34	24	– 29	40	29	33	15	13	73	66	– 9
Hungary	16	11	10	– 10	25	16	7	– 54	59	39	32	– 17	– 5	66	49	– 25
Iceland	13	0	0	– 17	0	0	0	ne[a]	87	2	2	– 18	– 34	2	2	– 10
Iran	7	13	21	62	16	31	35	10	78	154	342	122	20	198	398	101
Ireland	10	3	3	– 7	33	11	8	– 24	58	19	16	– 19	– 24	34	27	– 20
Italy	20	84	78	– 7	26	108	94	– 13	53	218	196	– 10	– 6	409	368	– 10
Japan	21	225	202	– 10	28	291	224	– 23	51	541	477	– 12	– 13	1057	903	– 15
Kazakhstan	3	8	6	– 28	46	115	49	– 57	51	127	97	– 23	– 32	251	153	– 39
Latvia	1	0	0	– 24	1	0	0	23	97	15	10	– 36	– 23	16	10	– 35
Lithuania	7	1	1	– 11	23	5	1	– 75	70	15	13	– 12	– 8	21	16	– 26

Malaysia	18	11	17	59	25	15	20	33	57	34	80	135	50	60	117	96
Mexico	29	86	149	72	21	64	67	5	50	152	337	122	55	303	554	83
Netherlands	26	41	40	− 4	23	37	31	− 15	51	81	68	− 17	− 23	159	138	− 13
Norway	24	6	5	− 10	0	0	5	ne[a]	76	18	17	− 4	− 11	23	27	14
New Zealand	28	9	8	− 13	11	4	2	− 31	62	20	19	− 3	− 26	32	30	− 9
Poland	11	39	31	− 20	40	141	84	− 40	49	172	152	− 11	− 15	351	268	− 24
Portugal	20	8	8	− 6	34	14	12	− 15	46	19	28	46	50	41	47	15
Romania	28	44	35	− 19	33	51	21	− 59	38	59	68	14	22	154	124	− 20
Russia	8	149	121	− 19	46	850	249	− 71	46	860	621	− 28	− 22	1859	991	− 47
Saudi Arabia	29	49	75	53	22	37	43	17	49	83	137	64	− 21	169	255	51
Singapore	28	9	14	50	39	13	17	25	33	11	14	26	− 5	34	45	33
Slovakia	8	4	4	− 12	16	8	5	− 39	77	42	28	− 33	− 35	54	37	− 32
Slovenia	10	1	1	− 18	34	4	2	− 47	55	7	6	− 9	− 5	13	10	− 23
South Africa	19	57	106	85	45	136	127	− 7	35	106	199	88	13	299	432	44
South Korea	26	63	119	90	16	38	45	19	58	137	171	25	5	238	335	41
Spain	22	48	43	− 9	29	62	47	− 25	49	105	123	17	17	215	213	− 1
Sweden	18	10	9	− 10	7	4	2	− 32	75	39	36	− 9	− 15	52	47	− 10
Switzerland	8	4	4	− 6	1	1	1	17	90	40	33	− 17	− 26	44	37	− 16
Thailand	11	10	18	74	34	32	42	32	55	52	166	219	167	94	226	139
Turkey	14	19	34	77	20	27	21	− 21	66	91	216	138	70	137	272	98
Ukraine	12	73	53	− 28	24	146	76	− 48	64	391	287	− 27	− 28	610	416	− 32
United Kingdom	13	78	71	− 9	35	205	160	− 22	52	305	210	− 31	− 26	588	441	− 25
United States	16	874	834	− 5	34	1887	1444	− 23	51	2844	1972	− 31	− 43	5605	4250	− 24
Total[b]	19	3659	4673	28	31	5998	4483	− 25	50	9735	14776	52	23	19392	23932	23

[a] Not estimated as the extremely low emission figure in 1990 resulted in an extraordinarily high growth percentage.

[b] Excluding European Union as a whole.

partial reduction objectives result from our criteria that were specified previously. The largest reduction percentages in the power-producing sector (Table 5) were established for Eastern Europe and the former Soviet Union, varying from − 75% (Lithuania) to − 32% (Czech Republic).

In North America fuel mix in power consumption differs. Contrary to the United States, Canada currently has a relatively small share of fossil fuels in power generation (IEA, 1998). Therefore the 30% reduction in fossil fuels does not affect Canada's CO_2 emissions in the power sector as much as it does for instance the US emissions in this sector and the partial reduction objective is less tight.

For the European Union partial objectives vary from − 38% (France) to − 13% (Italy). Norway's and Iceland's partial allowance objective in the power sector turned out to be exceptionally high as its 1990 emissions here were almost zero. Their growth in electricity consumption exceeds the presumed growth in renewable capacity (8% on top of 1990 capacity) and is taken to be covered to a large extent by CHP, which causes an increase in the assigned emissions.

The larger reduction figures for France and Belgium may seem odd, since these countries have large shares of nuclear power. It must be noted however that nuclear energy does not affect the reduction objective as its share is assumed to be constant. The reduction percentages are determined only by the growth in power consumption, the decrease in solid and liquid fossil fuels, and by the alterations in the shares of CHP, natural gas and renewable energy (see Appendix A). For the developing countries less strict reductions or even growth percentages are calculated starting from − 7% (South Africa). China is assigned a + 18% objective. China's economy is assumed to grow fast within the time frame analysed according to the IIASA/WEC scenario (1998) that we used. The relatively high partial objectives for developing countries must be ascribed to their high growth. According to our criteria this growth is not made up for by CO_2 free sources as renewable and nuclear energy, but instead is met largely by an increase in natural gas-based capacity.

Very high CO_2 growth numbers are assigned to countries with a high share of renewable energy, such as Iceland, Norway and Brazil. Their growth is not covered fully by renewables but instead will be covered partly in 2015 by gas and CHP.

4.3. The domestic sectors

Reductions in the domestic sectors (Table 6) are determined by the reduction in emissions per capita on one hand, which is determined by the 1990 per capita emission and the 2030 convergence level, and population growth on the other. Partial emission allowances of

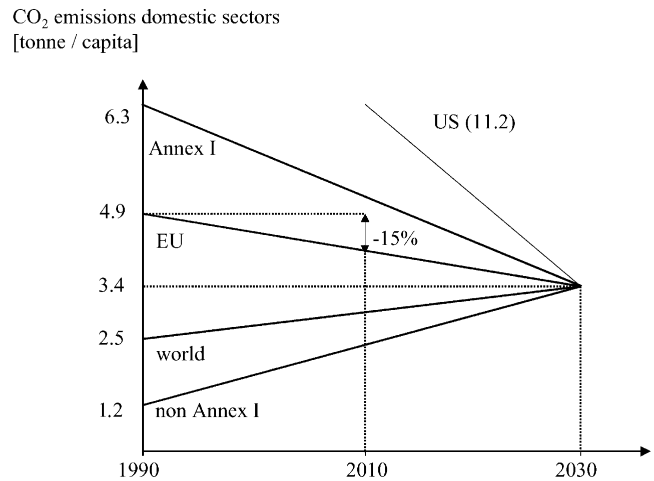

Fig. 2. Assumed convergence of CO_2 emissions in the domestic sectors for Annex I, non-Annex I, European Union, United States, and the world.

domestic emissions per capita are highest in the United States (− 42%) and Canada (− 39%). Allowances of per capita emissions in Eastern Europe and the former Soviet Union vary from − 35% (Slovakia) to + 22% (Romania). Energy efficiency in these countries is still poor so that there is quite a potential in the domestic sectors for carbon emissions reductions. For some countries in EE or FSU data may not be complete. 1990 per capita emissions in Lithuania, Bulgaria and Romania might have been underestimated, which results in large positive figures for the per capita reduction targets in these countries. In the European Union per capita emission reductions (i.e. growth) vary from − 30% (Germany) to + 50% (Portugal) which is caused by differences both in climate and standard of living. Almost all developing countries are assigned a per capita emission growth, although Singapore gets a − 5% per capita reduction target, as its 1990 per capita emission level was slightly higher than the 3.44 t CO_2/capita convergence level.

4.4. National reduction objectives

National emission allowances are determined by the partial reduction objectives in the three sectors on one hand and the relative size of the three sectors on the other. Fig. 3 and the far right column of Table 6 show the resulting differentiation of commitments for the year 2015. The sum of the emissions of the 48 countries results in a 8% growth relative to 1990. National reduction objectives vary from − 47% (Russia) to + 2205% (Brazil).

The applied criteria results in the strictest objectives for countries of the former Soviet Union (− 47% to − 26%), followed by the countries in Eastern Europe (− 32% to − 20%). In these countries large reductions are anticipated in both the power-producing sector and

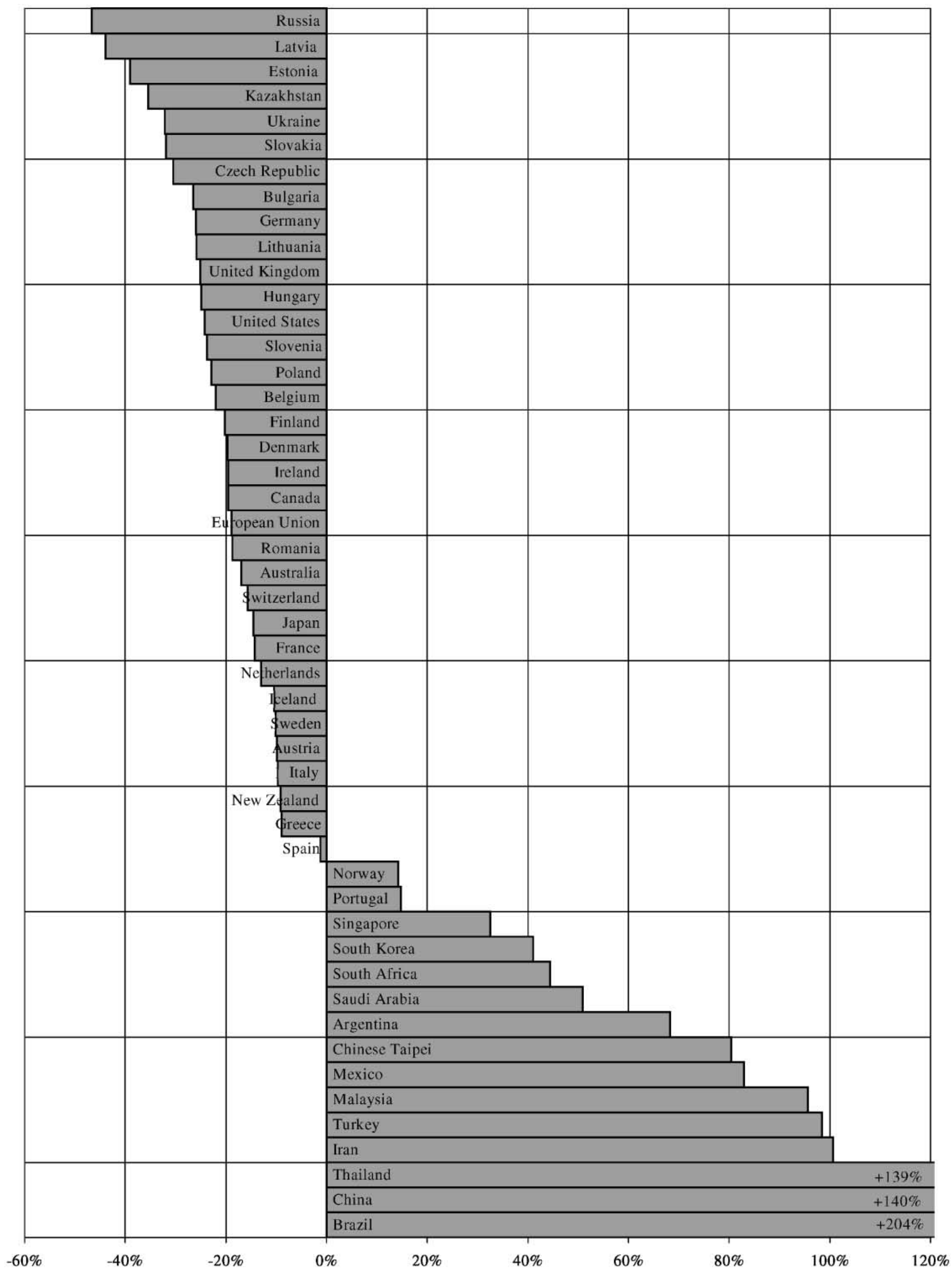

Fig. 3. Ranking of CO_2 emission reduction obligations of 48 countries and the European Union in a Triptych approach. All objectives are relative to 1990 emissions except for a number of Eastern Europe and Former Soviet Union countries (see footnote 6). Note that for bottom three countries the objectives exceed the scale of the X-axis.

the domestic sectors (see above). Canada and the United States get national objectives of −19% and −24%, respectively. Within the European Union national objectives vary from −26% (Germany) to +15% (Portugal). For the European Union as a whole a −19% target was calculated. For other western countries (non-EU) objectives vary from −17% (Australia) to +14% (Norway). The developing countries were all assigned a growth in CO_2 emissions, varying from +33% (Singapore) to +205% (Brazil). For the developing countries the

Table 7
Overall CO_2 emission reduction objectives and Kyoto objectives for five subsets of countries

	Present study 2015 (%)	Kyoto Protocol 2008–2012 (%)
OECD	− 16[a]	− 7
European Union	− 19	− 8
Economies in transition to a market economy	− 37	− 2
Annex I countries	− 24	− 5.2
Non-Annex I countries[b]	+ 140	na.
All countries	+ 23	na.

[a]Including OECD-members Mexico, Korea, Turkey; average objective would be − 18% without these countries.
[b]Included in this study.

domestic sector appears decisive, which is a direct consequence of the assumption that there will be a convergence by 2030 across all countries. The convergence approach in this sector involves that these countries can make up for their long way behind in development and CO_2 emissions.

Table 7 gives reduction objectives for five subsets of countries and the average objectives that have been established in the Kyoto Protocol. The Kyoto objectives were output from the negotiation process, whereas our calculated objectives may serve as input for future negotiations. The calculated objectives turned out stricter than the allowances that have been laid down in the Kyoto Protocol. In Fig. 4 the reduction objectives for the Annex I countries that we calculated are compared to the commitments as agreed on in Kyoto 1997. It was to be expected that the Triptych objectives turn out stricter because the target year 2015 is further ahead than the Kyoto budget period. This means that it is logical that the points in the diagram are left of the diagonal line through the origin. However if the calculated objectives would be comparable to the Kyoto targets most of the points would be closer to the line. In other words the degree to which calculated objectives are stricter than the Kyoto targets is larger than can be explained by the further remote target year.

5. Comparison with previous Triptych calculations

Although we applied more or less the same criteria as Phylipsen et al. did in their study for the European Union (1998b), the outcome for the various countries within the European Union appeared different. Table 8 summarises the differences between the criteria we apply in this study and the criteria Phylipsen et al. used for the European Union. An important difference is the difference in target years. As in the present study objectives are calculated for the year 2015 the overall growth until the target year will be larger, which will result in larger reduction percentages for some and larger growth figures for other countries.

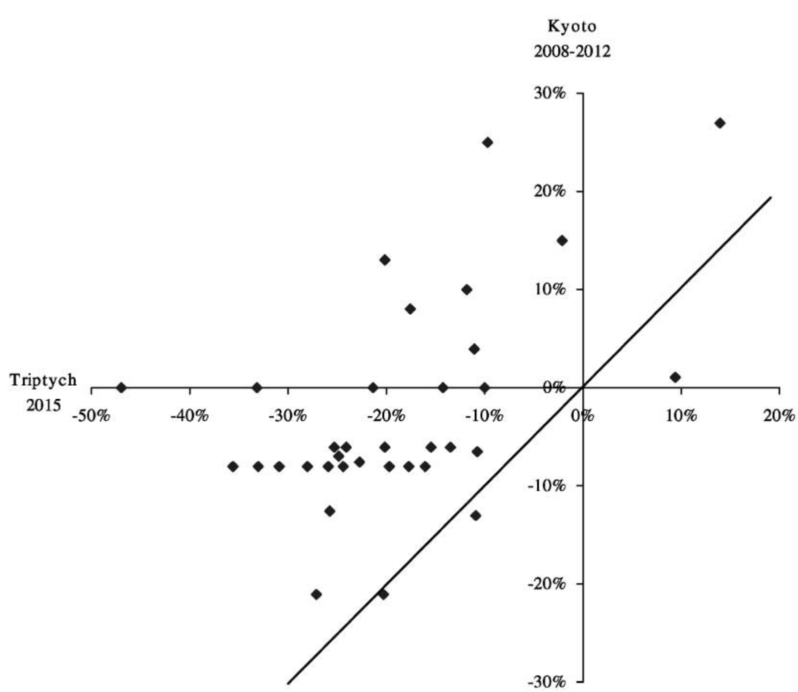

Fig. 4. Reduction objectives for Annex I countries as agreed in the Kyoto Protocol for the budget period 2008–2012 and as calculated according to Triptych.

Table 8
Comparison of reduction criteria in Triptych calculations for differentiation of commitments in the European Union (Phylipsen et al., 1998b) and in the present study

Target year	EU Phylipsen	Present study	
	2010	2015	
Heavy industry			
Annual physical production growth rate	1.2% for all EU members	EU	1.1%[a]
		OECD	1.0%[a]
		Eastern Europe/Former USSR	0.5%[a]
		developing countries	
Efficiency improvement rate	−1.29%[b]	−1.5%	3.9%[a]
	Regards reduction of specific energy consumption {GJ/t}	Regards reduction of specific CO_2 emission {Mt CO_2/t}	
Decarbonisation rate	−0.17%	Included in carbon-efficiency improvement rate (see above)	
Power			
Growth rate	1.9% for Cohesion Fund countries[c] 0.9% for others	1.9% for the EU; for others see Table 3	
Reduction output solid fossil fuel	−65% for UK and Denmark −50% for Germany −30% for others	−30% for all	
Nuclear	According to Conventional Wisdom scenario (Capros et al., 1995)	Share equal to 1990 share	
Renewable energy	1990 capacity and 6.56% of 2010 output	1990 capacity and 8% of 2015 output	
Domestic sectors			
Convergence level	Convergence to 2.96 t/c in 2030	Convergence to 3.44 t/c in 2040	
Degree-day correction	Yes	No	

[a] Weighed averaged based on 1990 emissions in the six different subsectors over the entire region.
[b] −0.66% for 1990–1995, −1.5% for 1995–2010.
[c] Greece, Ireland, Portugal, Spain.

Table 9 shows the distribution that Phylipsen et al. (1998b) established.[12] For the European Union as a whole they calculated a −13% objective, whereas in this study −19% results. There are several causes for this difference: different target years, different data sources, different growth assumptions and slightly different criteria (see Table 8). National targets within the European Union that result from this study are tighter for all Member States. This must be ascribed to differences in both data and criteria.

In order to assess to what extent differences are caused by differences in criteria and to what extent they must be ascribed to differences in data, we repeated our calculations with the data Phylipsen et al. used. They took data from Capros et al. (1995). Table 9 presents the reduction objectives for 14 countries of the European Union for three sets of Triptych calculations. For each sector the far-left column gives the objectives that resulted from the European Union study from Phylipsen et al. The middle column gives the objectives that result if the criteria from the present study are combined with the data from Capros (1995) and the far-right column shows the reduction objectives that resulted from the present study with IEA data. The difference between the study from Phylipsen et al. (far left) and the present study with Capros data (middle) can be ascribed to differences in criteria. The differences between the results in the middle and far-right column are caused by data differences only. In the following we will compare the three columns for each of the subsectors to assess the relative importance of the different criteria and the different data for the resulting partial allowances.

The energy-intensive industry. For most countries the use of slightly different criteria in heavy industry results in tighter partial objectives in the present study. This is caused mainly by the further remote target year we used (2015 vs. 2010). In addition the criteria in the present study result in differentiated partial allowances because we applied differentiated growth rates for the six subsectors. Using IEA instead of Capros data in the present study resulted in looser objectives, although to a varying extent. Differences in partial allowances related to data

[12] This distribution represents their base case except for heavy industry. The reason for this is that in their base case Phylipsen et al. assumed a differentiated growth for Cohesion Fund and non-Cohesion Fund countries, whereas we apply a uniform growth rate within the European Union. For the sake of comparability Table 9 shows Phylipsen's partial objectives in heavy industry accounting for equal production growth rates in all countries in the European Union.

Table 9
Partial reduction objectives {%} and overall national objectives for 14 countries in the European Union[a] according to the European Union study from Phylipsen et al. (1998b) (base case) and the present global study for 48 countries with two different data sets (Capros et al., 1995; IEA, 1997a; IEA, 1998)

Study	Heavy industry			Power			Domestic			Total			
Data from:	Phyl. Capros (%)	This study Capros (%)	IEA (%)	Phyl. Capros (%)	This study Capros (%)	IEA (%)	Phyl. Capros (%)	This study Capros (%)	IEA (%)	Phyl. Capros (%)	This study Capros (%)	IEA (%)	IEA (%)[b]
Austria	−6	−12	−11	0	−14	−6	−6	−11	−11	−7	−12	−10	*−4*
Belgium	−6	−13	−11	−14	−39	−34	−22	−28	−23	−16	−26	−22	*−16*
Denmark	−6	−10	−8	−19	−23	−24	−10	−16	−18	−16	−18	−20	*−14*
Finland	−6	−9	−8	−8	−27	−36	−7	−16	−18	−11	−19	−20	*−15*
France	−6	−14	−8	−32	−41	−38	−11	−15	−14	−12	−18	−14	*−8*
Germany	−6	−12	−7	−29	−31	−35	−16	−24	−27	−24	−25	−26	*−21*
Greece	−6	−22	−11	−11	−33	−29	3	14	15	2	−14	−9	*−3*
Ireland	−6	−29	−7	12	−18	−24	−17	−20	−19	−4	−20	−20	*−14*
Italy	−6	−11	−7	−11	−15	−13	−10	−7	−10	−5	−10	−10	*−4*
Netherlands	−6	−7	−4	−8	−14	−15	−13	−19	−17	−10	−15	−13	*−7*
Portugal	−6	−11	−6	12	−17	−15	28	51	46	22	11	15	*23*
Spain	−6	−11	−9	14	−28	−25	4	13	17	11	−5	−1	*6*
Sweden[c]	−6	−16	−10	404	−15	−32	−9	−16	−9	16	−16	−10	*−4*
United Kingdom	−6	−12	−9	−31	−24	−22	−15	−20	−31	−20	−21	−25	*−20*
European Union	−6	−12	−8	−19	−28	−28	−11	−15	−18	−13	−19	−19	*−13*

[a] Luxembourg has not been considered here. Note that the European Union total for the Phylipsen European Union study does include Luxembourg, whereas the present study does not.
[b] Reduction objectives according to this study (second column from the right) downscaled to an overall −13% reduction target for the EU.
[c] Large growth figure as Sweden's policy in that time to phase out its entire nuclear capacity was anticipated on.

are especially large (i.e. over 5% points) in France, Germany, Greece, Ireland and Sweden. This is caused mostly by different emission data for the chemical industry (all), the energy branch (Germany) and the building materials (Ireland). All in all different data and criteria result in stricter objectives for all countries in the European Union but the Netherlands. The reason for this is the sizeable Dutch chemical industry, which in the present study was assigned a large growth rate (Table 2).

In the power-producing sector the criteria in the present study result in tighter objectives for almost all Countries in the European Union (except the UK). There is a set of varying reasons for this. First, the present study does not include current nuclear policies, which has a tightening effect on the objectives for Belgium, Germany, Finland and Sweden. Next, current policies on the use of coal are not anticipated on, which has a loosening effect on the objectives for Denmark, Germany and the United Kingdom. An important effect stems from the use of different growth rates and a different target year. Phylipsen et al. set a total growth of 48% and 20% in 20 yr for Cohesion Fund and non-Cohesion Fund countries, respectively, whereas in the present study a total growth of 25%[13] over 25 yr applies. Obviously our growth assumption results in tighter partial allowances for the Cohesion Fund countries. Finally, we anticipate a much higher increase in efficiency for power generation in CHP and regular gas generation. We assume 70% shadow efficiency (see Appendix C) for all CHP capacity and a converging average efficiency for gas at 60% in 2015, whereas Phylipsen et al. took efficiencies varying from 38% to 44% in 2010 for both CHP and regular gas as a point of departure. Our more ambitious efficiencies result in tighter objectives for all Member States.

The effect of using IEA data instead of Capros data differs for the various Countries in the European Union. It turned out that Capros data on power generation include autoproduction whereas our data represent public generation only. We included autoproduced power generation in the SEC reduction approach in heavy industry. This causes shifts in partial allowances that are especially important for countries with large shares of autoproduction. In Sweden for instance, fossil-fuel consumption in public power generation is very limited. Therefore the exclusion of autoproduction in this study causes a much tighter partial allowance for this country. It must be noted however that the inclusion of autoproduction may affect the outcome in various ways. Partial allowances may become looser because of higher levels for solid and liquid fossil-fuel input. On the other hand the output from nuclear and renewable energy becomes higher too, as these are determined as a share of

[13] Resulting from a 1.9%/yr economic growth rate and an annual reduction of electricity demand by 1% due to increased efficiency.

the total output, which also becomes higher in case autoproduction is included. The net effect varies from country to country depending on the fuel mix.

For Ireland the higher 1990 emission level in IEA statistics compared to Capros data causes the larger reduction rate. The uncertainty on the 1990 emission from Irish regular power generation stems mainly from the extent to which peat is included in the statistics.

In the domestic sectors differences between the European Union study from Phylipsen and the present study with Capros data reflect mainly the omission of climate correction in the present study. The criteria from the present study result in looser partial objectives for the warm Mediterranean countries and tighter objectives for the other Countries in the European Union. The further remote target year that we use has a lowering effect on the partial allowance in the domestic sectors for all European Member States. If in addition the Capros data are substituted by IEA data tighter objectives result for all countries. The reason for this is that per capita emissions in the domestic sectors calculated with IEA data are higher. In the domestic sector differences in data on average were more important than in other sectors.

Total reduction objectives established in the present study and by Phylipsen et al. can be compared in the first and the fourth column from the right, respectively. In the far-right column we downscaled our objectives so as to obtain an overall − 13% target for the EU. For most countries the differences are under 5% points. Resulting overall objectives in this study deviate strongly for Ireland Sweden. This is caused mainly by the different partial objectives in the power sector.

6. Discussion

Although our results are interesting there are some remarks that need to be made with respect to the data and methodology used. In the following we will discuss data, compare our results with previous Triptych calculations and reflect on the methodology.

6.1. Data

One major problem while calculating a differentiation of commitments is the availability of good data. Uncertainties are introduced by the poor quality of data for some countries, especially in Central and Eastern Europe, the former Soviet Union and developing countries. For instance the comparison of electricity output and fuel input in power generation in these countries indicates that data are not fully reliable here.

For this exercise we used IEA data, which probably is the best there is for such a large collection of countries. However, IEA data are not always fully reliable either and in some cases may be incomplete. It is conceivable that National Communications under the UNFCCC may contain better data. However, by and large national communications are available for the Annex I countries only and moreover the data they offer are often too aggregated. For instance there is no distinction in heavy and light industry.

A special point that needs attention is the data on power production in Eastern Europe and in the former Soviet Union. The calculation of generating efficiencies in these countries resulted in some very unlikely figures, which we did not use in our calculations (e.g. for liquid fossil fuels 7% in Slovenia and 124% in Latvia) indicating that data definitely need improvement here.

6.2. Scenarios

The choice for a particular scenario is a crucial one as growth assumptions may affect the outcome of the calculations to a large extent. Although in general scenarios do contain a certain degree of expert judgement, a scenario is by definition surrounded by large uncertainties, as it is only an estimation of future developments. Business-as-usual scenarios do not include unexpected developments in the growth of the economy, physical production and population. Therefore large uncertainties might be introduced with respect to future physical production and economic growth.

We tested the effect of altered growth assumptions. For these countries we decreased growth rates for physical production (Table 2) and the economy (Table 3) by 1% point. Naturally the resulting objectives became stricter for all countries, but the degree to which this happened differed. For countries in Eastern Europe and the former Soviet Union the targets became stricter by 1–8% points respectively, Latvia and Romania. For the major part of the western world targets became stricter by 3 to 12% points (Switzerland and New Zealand, respectively). Only for Norway the lower growth assumptions resulted in an objective that was lower by 25% points.

The effect of lower growth rates was most striking in developing countries, where targets become stricter by 13 (Malaysia and Thailand) to 26% points (Brazil). For the three developing countries that were assigned the largest growth objectives the targets under lower growth assumptions are mentioned in Table 10. It can be concluded that in general reduction targets may alter substantially if growth rates are decreased by only 1% point. However, although reduction targets for developing countries do turn out stricter they remain in the same order of magnitude.

The targets for developing countries are high compared to other non-intervention scenarios. IPCC's Working Group III database on emission scenarios (IPCC, 2000) contains non-intervention scenario's for China that vary roughly between − 70% and + 200% for China. The median of this range is 86% while 80% of

Table 10
Overall national reduction objectives according to the Triptych approach for three developing countries for (1) a base case distribution and (2) a distribution with growth rates for physical production and the economy that are lower by 1% point

	Base case (%)	Growth rates lower by 1% point (%)
China	+ 139	+ 120
Thailand	+ 140	+ 126
Brazil	+ 205	+ 179

Table 11
Overall national reduction objectives according to the Triptych approach for three developing countries. The three columns represent three convergence periods for CO_2 emissions in the domestic sectors

	2030 (%)	2050 (%)	2100 (%)
China	+ 140	+ 107	+ 78
Thailand	+ 139	+ 103	+ 70
Brazil	+ 205	+ 159	+ 116

the estimations are below 120%. It is especially the accelerated convergence of emissions in the domestic sectors (i.e. by the year 2030) that causes the fast increase in emissions calculated in this article. Table 11 shows overall reduction objectives for the three countries with the highest allowances that result if convergence of CO_2 emissions is not due until 2050 and 2100. Convergence by the year 2100 reduces overall allowances considerably.

We also tested what the consequences would be of an alternative treatment of OECD members Korea, Mexico and Turkey in the energy-intensive industry. Initially we classified these countries as developing countries in heavy industry because their economies are not as mature as those of other OECD countries. On the other hand they have been developed much further than most of the other developing countries. Physical production growth in developing countries as assumed in this study is much higher than growth within the OECD (Table 2). Table 12 shows what overall national objectives would result if these countries were assigned the same physical growth rates in heavy industry as other OECD countries. Obviously a substantial adjustment of the assigned physical production growth affects the resulting national target to a large degree.

6.3. Criteria

The partial allowances in the power sector give cause for criticism of the criteria applied in this sector. We do not take into account countries' potential for renewable energy. On the other hand renewable energy in 2015 takes only a limited share on top of 1990 capacity. In addition, renewable sources are relatively costly ways to produce electricity and it can be considered fair to distribute the costs for renewable energy evenly.

Table 12
Overall national reduction objectives according to the Triptych approach for three OECD members for (1) a base case distribution with physical production growth in heavy industry equal to other developing countries (DCs) and (2) a distribution with physical production growth equal to other OECD members

	Growth in heavy industry equal to other DCs (base case) (%)	Growth in heavy industry equal to other OECD (%)
Mexico	+ 83	+ 60
South Korea	+ 41	+ 14
Turkey	+ 98	+ 86

Another point is that there are a number of countries such as China or Saudi Arabia that have large reserves of fossil fuels. As fossil reserves are near at hand in such huge amounts it will be very unattractive (and probably innegotiable) for these countries to leave their resources underexploited to a large extent. On the other hand solid and liquid fossil fuel reserves are sometimes found together with natural gas which may leave these countries still a possibility for CO_2 emission reduction. In China analysis of geologic formations has led to expectations that gas reserves are much larger than current discoveries indicate (Sinton et al., 1996). However natural gas has been relatively neglected both in exploration and development. Overall it seems desirable to adjust the criteria for the power-producing sector in a way that takes into account countries' potential for renewable energy as well as their indigenous sources.

Furthermore, it would be interesting to investigate the effect of a further remote convergence year in the domestic sectors. As differences in welfare are larger on a global scale than within the European Union only more time is needed to let per capita emissions converge to the same level. Unfortunately it is difficult to assess on what time span convergence will be feasible. Therefore sensitivity analyses are all the more important.

In addition domestic power consumption could be included in the domestic sectors. This means that electricity production for buildings would be subjected to a convergence approach together with the domestic emissions from fuels. The reason for doing so would be that power consumption in households and the service sector is very much related to the size of the population and standard of living, which justifies a convergence approach.

6.4. National circumstances

Although we took into account a range of national circumstances, there are various factors that we did not consider in this exercise. One of them is climate:

colder countries need more energy for heating whereas warmer countries need more energy for cooling. Phylipsen et al. corrected for climatic differences using the number of degree-days.[14] The reason that we did not include climatic differences in our calculations is that as yet we do not dispose of data on degree-days for the entire selection of countries. However, we did check the influence of including climatic differences on the overall national allowances for fourteen Countries in the European Union. For each of these countries we established corrected 1990 emissions in the domestic sectors, to represent emissions that would have occurred if each of the countries had had an average European climate. We found the largest increase in national allowance for Greece (+ 1.8% points) and the largest decreases for Finland and Sweden (− 1.5% and − 1.7% pts, respectively). For most countries the difference turned out smaller than 1% point.[15] On a global scale climatic differences are larger than within the European Union though. Therefore it is desirable to further investigate the influence of including climate both for heating and cooling as a national circumstance in a global differentiation scheme.

Another factor that would be worth including in the calculations is differences in energy efficiency in heavy industry. Differences in energy efficiency are large (Worrell et al., 1994) and it is recommended that they are accounted for in any differentiation scheme (Groenenberg et al., 1999).

It must also be noted that this differentiation scheme has been based on CO_2 emissions only, which is an important shortcoming. It is well known that globally CH_4, N_2O and the halocarbons[16] contribute in the order of 40% to radiative forcing whereas the contribution of CH_4 and N_2O only is estimated around 25% (IPCC, 1996). Unfortunately the availability of data for non-CO_2 gases is even more limited than for CO_2. So far, large uncertainties exist in emission inventories and current inventory practices are still under discussion. However, as the emission of non-CO_2 greenhouse gases varies over different countries and reduction potentials are substantial (Blok and De Jager, 1994) the inclusion of these gases will probably affect the ranking of countries in a differentiation scheme.

6.5. *Effectiveness*

We calculated the overall shift in CO_2 emissions compared to 1990 levels as + 8% for the sum of the 48 countries included.

An important question in this differentiation exercise is to what extent the overall level of reductions would be sufficient to curb the trend of global warming. In order to answer this question the short-term overall reduction level would have to be off set against the resulting long-term CO_2 concentrations in atmosphere and the accompanying climatic indicators such as temperature increase and sea level rise. To this end, Swart et al. (1998) developed the Safe Landing Concept, which resulted in ranges of safe emission levels for the short term (i.e. until 2010). These are levels from which long term (i.e. 2100) climate targets would still be achievable somehow, using tighter or looser reduction policies.

According to their results the 8% increase by the year 2015[17] in the 48 countries included in this study would be just within the safe emission corridor if one would consider 0.10°C/yr[18,19] temperature change acceptable. This

[14] Degree-days give an indication of the coldness of the weather by measuring how often daily averaged temperatures are below a reference (room) temperature and to what extent. The number of degree-days is defined as the sum of the difference between outdoor temperature and the reference temperature during each day at which the outdoor temperature is below that reference temperature in the course of 1 yr (Schipper et al., 1985). Likewise, degree-days could indicate the heat of the climate.

[15] To this end we multiplied a part as large as 80% of the 1990 emissions in the commercial and residential subsectors (i.e. not the entire domestic sectors!) with a climate correction factor in order to correct 1990 emissions either upwards (warm countries) or downwards (cold countries). This factor was the ratio of the number of cooling degree-days in a country and the average number of cooling degree-days within the European Union. Note that we use the average European climate as a reference.

[16] Note that only HFCs PFCs and SF_6 are included in the Kyoto Protocol.

[17] This 2015 increase corresponds to a somewhat lower increase percentage for 2010. In addition, the global increase in CO_2 emission may be less than the increase in our selection of countries, as our study excludes the countries that are furthest behind in development and are not likely to catch up in the near future. Under the IS92a scenario total non-Annex I growth in CO_2 emissions from fuel combustion until 2010 ranges from + 58% for Latin America to + 135% for South East Asia (IPCC, 1996). We calculated 137% for the sum of the 13 non-Annex I countries in our study but did not estimate the growth in emissions from other non-Annex I countries.

[18] Apart from a criterion on the rate of temperature change Swart et al., used a set of long-term climate criteria. (1) IPCCs best guess for climate sensitivity (2.5°C); (2) a maximum temperature rise of 1.5°C from 1990 onwards; (3) a maximum sea-level rise of 30 cm by the year 2100 and (4) a feasible emission reduction objective of 2.0%/year at most. It followed that global CO_2 equivalent emissions for Annex I should not increase by more than a quarter over 1990 levels or by roughly 15% depending on the allowed rate of temperature change (respectively, 0.15 and 0.10°C/yr). A rate of 0.15°C resembles the average value of a 1.5°C temperature increase over the next century, whereas a maximum rate of temperature change of 0.10°C corresponds to a more ecological, risk-aversive perspective. These percentages are based on the assumption that non-Annex I emissions would follow IPCCs IS92a scenario and represent utmost limits of safe emissions. The authors note that meeting long-term climate targets is still possible with these emissions in 2010 but that opportunities and possibilities for increases in emissions, especially for the non-Annex I countries, are limited.

[19] Although Swart et al., base their analysis on CO_2 equivalent emissions we compare their results with our calculations for CO_2 only assuming that emissions of non-CO_2 gases alter in the same way as CO_2 emissions.

criterion corresponds to an ecological and risk aversive criterion for the rate of temperature change.[20]

In an additional calculation we examined to what extent criteria would have to be adjusted to stabilise 2015 CO_2 emissions at the 1990 level. It turned out that this would require for instance the following criteria: (1) a reduction of 3% of the specific carbon emission in heavy industry, (2) a reduction by half of solids and liquids and a 25% share of renewable energy in the power sector and (3) a convergence level of 2.9 t/c in the domestic sectors.

7. Conclusions

In this study we established a differentiation of CO_2 emission reduction obligations for a selection of 48 countries. To this end we used the Triptych approach that serves as a tool to rank countries in a differentiation scheme. The approach accounts for a number of varying national circumstances. Population size and population growth, standard of living as estimated by CO_2 emissions per capita, economic structure, generating efficiency and fuel mix were all taken into account.

In spite of the uncertainties introduced by the data and the scenarios we used there are some tentative conclusions that can be drawn from these preliminary calculations. With the criteria used the average reduction objective for the OECD will be somewhere between −10% and −20%. For economies in transition to a market economy our calculations indicate on average a reduction between −30% and −50%. For the developing countries we established increases varying roughly from +40% to +200% increase in CO_2 emissions on average, very much depending on growth rates in the economy and physical production and to an even larger extent on the rate of global convergence of domestic emissions.

The problems we encountered in our calculations give reason for additional study. Future work should include more study on the expected growth of developing countries in order to obtain a better estimate for the year of convergence in the domestic sectors and more founded growth rates in heavy industry and the power-producing sector. Other growth scenarios for these countries can be used for sensitivity analyses with the Triptych approach. Another problem we encountered regards the criteria we applied in the power-producing sector. These are insufficiently fit for the wide global variety of fuel mixes in power generation and need adjustment in a way that takes into account countries' potential for renewable energy as well as their indigenous fossil-fuel supplies. Additional national circumstances that may be worth including in future Triptych calculations are climate, energy efficiency in heavy industry and the reduction potentials for non-CO_2 greenhouse gases.

Finally, the overall reduction level that results from the reasonable criteria we applied involves a growth of emissions by a quarter in the year 2015 for the sum of the 48 countries included. This seems just enough to constitute a first step towards meeting long-term climate targets.

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Appendix A. Formulae

We used the following formulae to incorporate the national circumstances in our differentiation scheme.

The energy-intensive industry: The allowance in the energy-intensive industry were calculated according to

$$A_{\mathrm{ind},2015} = E_{\mathrm{ind},1990}(1+g)^n(1-e_i)^n, \qquad (A.1)$$

where $A_{\mathrm{ind},2015}$ is the partial allowance for heavy industry in the year 2015 (Mt CO_2), $E_{\mathrm{ind},1990}$ the emission from heavy industry in the year 1990 (Mt CO_2), g the annual growth rate of physical production (%) (see Table 2), and e_i the annual efficiency improvement (expressed as the reduction of the average specific energy consumption).

The power-producing sector: Total electricity consumption in 2015 was estimated according to

$$\mathrm{EL}_{\mathrm{tot},2015} = \mathrm{EL}_{\mathrm{tot},1990}(1+g)(1-\mathrm{rdei})^n. \qquad (A.2)$$

Electricity generated by various sources in 2015 was calculated as follows:

$$\mathrm{EL}_{\mathrm{coal},2015} = 70\%\mathrm{EL}_{\mathrm{coal},1990}, \qquad (A.3)$$

$$\mathrm{EL}_{\mathrm{liq},2015} = 70\%\mathrm{EL}_{\mathrm{liq},1990}, \qquad (A.4)$$

$$\mathrm{EL}_{\mathrm{nucl},2015} = \mathrm{EL}_{\mathrm{tot},2015}\frac{\mathrm{EL}_{\mathrm{nucl},1990}}{\mathrm{EL}_{\mathrm{tot},1990}}, \qquad (A.5)$$

$$\mathrm{EL}_{\mathrm{renew},2015} = \mathrm{EL}_{\mathrm{renew},1990} + 0.08\mathrm{EL}_{\mathrm{tot},2015}, \qquad (A.6)$$

$$\mathrm{EL}_{\mathrm{CHP},2015} = \min(\mathrm{EL}_{\mathrm{tot},2015} - \mathrm{EL}_{\mathrm{coal},2015} - \mathrm{EL}_{\mathrm{liq},2015} - \mathrm{EL}_{\mathrm{nucl},2015} - \mathrm{EL}_{\mathrm{renew},2015}, 0.15\mathrm{EL}_{\mathrm{tot},2015}), \qquad (A.7)$$

[20] An important uncertainty is introduced by the choice for a climate sensitivity level of 2.5°C, which is at the lower end of the IPCC range (1.5–4.5°C). If the temperature increase for a doubling of CO_2 equivalent concentrations at a certain moment would turn out to be higher than 2.5°C this would decrease safe emissions levels substantially.

$$\mathrm{EL}_{\mathrm{gas},2015} = \min(\mathrm{EL}_{\mathrm{tot},2015} - \mathrm{EL}_{\mathrm{coal},2015} - \mathrm{EL}_{\mathrm{liq},2015} - \mathrm{EL}_{\mathrm{CHP},2015} - \mathrm{EL}_{\mathrm{renew},2015}\text{-}\mathrm{EL}_{\mathrm{CHP},2015},0), \quad (A.8)$$

where $\mathrm{EL}_{\mathrm{tot},y}$ is the total electricity consumption in year y (PJ), $\mathrm{EL}_{x,y}$ the electricity consumption by fuel x in year y (PJ), g the annual GDP growth rate (see Table 3), and rdei the reduction rate for reduced demand due to efficiency improvements, and n the number of years.

We estimated 2015 power generation efficiencies by interpolating between the 1990 efficiencies and a convergence level for the efficiency in 2030

$$\eta_{x,2015} = \eta_{x,1990} + (\eta_{x,\mathrm{conv}} - \eta_{x,1990})\tfrac{25}{40}, \quad (A.9)$$

where $\eta_{x,y}$ is the generation efficiency in conventional capacity based on fuel x (solids, liquids or gas) in year y (%), and $\eta_{x,\mathrm{conv}}$ the convergence of efficiency in the year 2030 in capacity based on fuel x (%).

Primary energy use in conventional and in CHP capacity was calculated as

$$\mathrm{PE}_{\mathrm{coal},2015} = \frac{70\%\mathrm{EL}_{\mathrm{coal},1990}}{\eta_{\mathrm{coal},2015}}, \quad (A.10)$$

$$\mathrm{PE}_{\mathrm{liq},2015} = \frac{70\%\mathrm{EL}_{\mathrm{liq},1990}}{\eta_{\mathrm{liq},2015}}, \quad (A.11)$$

$$\mathrm{PE}_{\mathrm{CHP}} = \frac{\mathrm{EL}_{\mathrm{CHP},2015}}{\eta_{\mathrm{CHP},2015}}, \quad (A.12)$$

$$\mathrm{PE}_{\mathrm{gas}} = \frac{\mathrm{EL}_{\mathrm{gas},2015}}{\eta_{\mathrm{gas},2015}}, \quad (A.13)$$

where $\mathrm{PE}_{x,y}$ is the primary energy use of fuel x in year y (PJ); $\eta_{\mathrm{CHP},2015}$ the shadow efficiency in CHP (see Appendix C).

Finally, we determined the partial allowance for the power-producing sector

$$A_{\mathrm{coal},2015} = \mathrm{PE}_{\mathrm{coal},2015}[(1 - f_{\mathrm{bc}})\mathrm{ef}_{\mathrm{hc}} + f_{\mathrm{bc}}\mathrm{ef}_{\mathrm{bc}}], \quad (A.14)$$

$$A_{\mathrm{liq},2015} = \mathrm{PE}_{\mathrm{liq},2015}\mathrm{ef}_{\mathrm{liq}}, \quad (A.15)$$

$$A_{\mathrm{gas},2015} = \mathrm{PE}_{\mathrm{gas},2015}\mathrm{ef}_{\mathrm{gas}}, \quad (A.16)$$

$$A_{\mathrm{CHP},2015} = \mathrm{PE}_{\mathrm{CHP},2015}\mathrm{ef}_{\mathrm{gas}}, \quad (A.17)$$

$$A_{\mathrm{power},2015} = A_{\mathrm{coal},2015} + A_{\mathrm{liq},2015} + A_{\mathrm{gas},2015} + A_{\mathrm{CHP},2015}, \quad (A.18)$$

where f_{bc} is the share of brown coal in coal iput in public electricity generation (%), ef_x the emission factor for fuel x (Mt CO_2/PJ), $A_{\mathrm{coal},2015}$ the allowance for coal-based electricity in the year 2015 (Mt CO_2), $A_{\mathrm{power},2015}$ the allowance for the power-producing sector in the year 2015 (Mt CO_2), and $A_{x,2015}$ the allowance for electricity from x based electricity (excl. coal) (Mt CO_2).

Domestic sectors: The partial allowance for the domestic sectors in 2015 was based on a convergence of per capita allowances by the year 2030

$$a_{\mathrm{pc},2015} = a_{\mathrm{pc},1990} - (a_{\mathrm{pc},1990} - a_{\mathrm{pc,conv},2030})\tfrac{25}{40}, \quad (A.19)$$

$$A_{\mathrm{dom},2015} = a_{\mathrm{pc},2015}P_{2015}, \quad (A.20)$$

where $A_{\mathrm{pc},2015}$ is the per capita allowance in the year 2015 (Mt CO_2), $A_{\mathrm{pc},2030}$ the convergence level for the per capita allowance by the year 2030 (Mt CO_2), P_{2015} the population in the year 2015, and $A_{\mathrm{dom},2015}$ the allowance for the domestic sectors in the year 2015 (Mt CO_2).

Appendix B. Generating efficiencies

Table 13 gives an overview of 1990 generating efficiencies for the countries included in this study.

Appendix C. Shadow efficiency for combined generation of heat and power (CHP or cogeneration)

Plants for combined generation of heat and power (CHP plants and cogeneration) produce both heat and electricity. To this end we have to allocate fuel input and emissions of CHP plants to these two products. In our approach, we allocate all the energy savings caused by CHP to the electricity part. This also means that we do not allocate any savings to the heat consumers (in fact we took this into account by assuming that the possible energy efficiency improvement rate in industry is only 1.5% instead of 2.0%, see Phylipsen et al., 1998c).

We calculate a 'shadow efficiency' for CHP power generation: the electricity output of CHP plants divided by the fuel input allocated to electricity production. We do this by subtracting from the fuel input to the CHP plant the fuel input that otherwise would have been needed for heat production.

$$\eta_{\mathrm{shadow,E,CHP}} = \frac{E_{\mathrm{CHP}}}{F_{\mathrm{CHP}} - H_{\mathrm{CHP}}/\eta_{\mathrm{regH}}} = \frac{\eta_{\mathrm{E,CHP}}}{1 - \eta_{\mathrm{H,CHP}}/\eta_{\mathrm{regH}}}, \quad (C.1)$$

where $\eta_{\mathrm{shadow,E,CHP}}$ is the shadow efficiency for electricity generation from CHP plants, F_{CHP} the fuel consumption by CHP plants, H_{CHP} the heat production from CHP, $\eta_{\mathrm{H,CHP}}$ the generating efficiency for heat by the CHP plants ($H_{\mathrm{CHP}}/F_{\mathrm{CHP}}$), $\eta_{\mathrm{E,CHP}}$ the generating efficiency for electricity generation by the CHP plants ($E_{\mathrm{CHP}}/F_{\mathrm{CHP}}$), and η_{regH} the generating efficiency for regular heat generation.

Table 13
Generating efficiencies for solid, liquid and gaseous fossil fuels in 1990. Data on electricity output and fossil fuel input are from (IEA, 1998) for OECD countries and from (IEA, 1997c) for non-OECD countries[a,c]

	Solid[b,c] (%)	Liquid (%)	Gas (%)
Argentina	30	25	27
Australia	36	36	33
Austria	38	41	38
Belgium	39	39	35
Brazil	25	28	21
Bulgaria	34	12	16
Canada	36	37	30
China	31	33	44
Chinese Taipei	37	39	33
Czech	39	34	28
Denmark	40	39	ne
Estonia	27	28	40
European Union	37	39	38
Finland	40	34	37
France	40	40	37
Germany	37	36	41
Greece	31	35	ne
Hungary	25	25	25
Iceland	ne	33	ne
Iran	ne	29	42
Ireland	41	37	36
Italy	39	40	36
Japan	41	41	39
Kazakhstan	21	23	18
Latvia	ne	ne	ne
Lithuania	ne	ne	ne
Malaysia	32	30	38
Mexico	37	34	33
The Netherlands	41	ne	40
Norway	30	30	ne
New Zealand	35	22	36
Poland	33	ne	ne
Portugal	38	39	ne
Romania	29	21	30
Russia	21	39	16
Saudi Arabia	ne	ne	51
Singapore	ne	30	21
Slovakia	35	ne	42
Slovenia	32	ne	ne
South Africa	37	ne	ne
South Korea	37	35	34
Spain	37	35	33
Sweden	31	25	ne
Switzerland	19	ne	ne
Thailand	35	32	29
Turkey	34	33	42
United Kingdom	37	37	ne
Ukraine	29	35	36
United States	35	34	33

[a]For most countries the 1990 generating efficiency was based on regular power production only. However, Eastern European countries often do not distinguish between regular and CHP power production in their statistics. Therefore, generating efficiencies here are based on the sum of regular and CHP inputs and outputs in most of these countries (Bulgaria (liquids and gas only), Estonia, Kazakhstan, Latvia, Lithuania, Poland, Romania, Russia, Singapore (gas only) Slovakia, Slovenia, Ukraine). In most cases we included heat in the calculation of the generating efficiency, at a quality factor of 0.175. (For a discussion on the valuation of heat in the output of CHP, see Phylipsen et al. (1998a). For the Netherlands, Norway, Poland, Sweden and Switzerland the generating efficiencies for solid fossil fuels were based on CHP only and corrected for heat, as data on regular electricity production were lacking. Phylipsen et al. (1998c) discuss generating efficiencies in a range of countries in more detail.

[b]For countries that use both hardcoal and brown coal the efficiency for solids is a weighed average (based on the outputs) of the hardcoal and brown coal efficiencies. Net caloric values (TJ/kt) for brown coal vary widely and were taken from (IPCC, 1995). As no value was reported for Slovenia we took the average value of Greece and Turkey for Slovenia, assuming that the vicinity of these countries brings about a comparable brown coal quality.

[c]For most countries the 1990 efficiencies are reported, except for Bulgaria (1991), Estonia, Latvia, Lithuania, Romania, Ukraine (1992), gas in Singapore (1992), Russia (1993).

Table 14
Conversion efficiencies for CHP equipment and for alternative heat production equipment (boilers) that result in values for the SFC_{CHP}[a]

	$\eta_{E,CHP}$ (%)	$\eta_{H,CHP}$ (%)	η_{regH} (%)	η_{CHP} (%)
District heating	48	32–37[b]	90–100	62–69
Industrial CHP (combined cycle)	42–45	20–34	90	54–72
Small industrial CHP (gas turbine)	35–38	47–50	90	73–86
Small-scale gas engine	32–40	50–54	100	64–87

[a]Van Dril et al. (1999).
[b]Excluding heat losses (10–20%) in the distribution system.

For state-of-the-art CHP equipment the conversion efficiency values are presented in Table 14.

From these figures we can obtain values for the shadow efficiency of ranges from 54% to 87%. We choose to use 70% as a shadow efficiency for electricity from CHP in our calculations.

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